

UNITED NATIONS CENTRE FOR HUMAN SETTLEMENTS (Habitat)

# **EARTH CONSTRUCTION TECHNOLOGY**

---

United Nations Centre for Human Settlements (Habitat)  
Nairobi, 1992



Mention of firm names and commercial products does not imply  
the endorsement of the United Nations.

## FOREWORD

In most rural areas of developing countries and in some urban low-income settlements, earth is the main material used for shelter construction. Under these circumstances, earth construction has often been characterized by dilapidated, temporary and unsafe structures. In fact, living examples of good, durable and attractive earth buildings are hard to come by, while the popularity of the material has dwindled to the extent that, even in circumstances where it should be the obvious choice in rural housing construction, preference has been given to relatively modern materials.

In principle, soil is not restricted to low-cost construction, but, rather, forms the basis of a technically sound engineering practice which is comparable to concrete technology or that of any of the popularly adopted building materials. Ultimately, a building material responds to clearly defined functional requirements in the construction process. The merit of earth in construction should be judged by its ability to fulfil a number of construction tasks - notably as a material for walls, floor, renderings and even for roofs. The issue of earth being a low-cost material is incidental and, indeed, an added advantage to these technically viable properties. For this reason, the material should be promoted alongside other conventional materials to the extent that professionals in the construction sector can make a choice for earth in preference over or as an alternative to comparable materials. It is along these lines that the objectives of wide-scale adoption of the material could be achieved while meeting the construction needs of low-income people.

Following this principle, earth construction faces an obvious disadvantage in comparison with other popularly adopted materials. There is only limited knowledge of good earth construction practice. The construction technologies which are predominant in the informal channels for artisan training are defective and inappropriate. In the conventional technical and professional training institutions, there is hardly any coverage of the subject of earth construction apart from basic civil engineering considerations. While architects, town planners, civil engineers, quantity surveyors and numerous sub-professionals in the construction sector have a role to play in promoting the use of earth, the foremost task is to fill a gap in their knowledge, i.e., to provide adequate technical information on earth construction for use by professionals in field implementation projects. It was for this purpose that a series of publications on earth construction was issued in the mid-1980s.

This series of publications was made up of four technical manuals on (a) basic principles of earth application; (b) design and construction techniques; (c) surface protection; and (d) production of components. The four manuals were complementary to each other, yet each, presented in a distinct and concise manner, responded to a specific component of the subject.



2552  
The manuals were intended for professionals dealing with projects on earth construction to serve as useful reference material and aids in actual field practice. The four have been brought together in the current publication for the benefit of a wider group of professionals, programme administrators and policy-makers who are concerned with the subject.

The preparation of the original manuals was based on an extensive project on earth construction technology undertaken by the United Nations Centre for Human Settlements (Habitat) in collaboration with the Government of Belgium. The Centre remains deeply grateful to Messrs. Hugo Houben and Guillaud Hubert, who were the principal consultants for the project.



**Dr. Arcot Ramachandran**  
Under-Secretary-General  
Executive Director

# Contents

Page

## PART ONE

### BASIC PRINCIPLES OF EARTH APPLICATION .....1

#### INTRODUCTION .....1

I.	FUNDAMENTALS OF SOIL SCIENCE .....	2
A.	Basic properties of soil .....	2
B.	Composition of solids in soil .....	3
C.	Soil identification .....	4
D.	Suitability of soils for construction .....	13
II.	PRINCIPLES OF SOIL STABILIZATION .....	14
A.	Basic considerations .....	14
B.	Methods of stabilization .....	16
C.	Suitability of soils for stabilization .....	18
III.	CHARACTERISTICS OF SOIL STABILIZERS .....	22
A.	Fibre .....	22
B.	Cement .....	23
C.	Lime .....	26
D.	Bitumen .....	29
E.	Resins .....	31
F.	Natural products .....	33

## PART TWO

### DESIGN AND CONSTRUCTION TECHNIQUES .....35

I.	BASIC CONSIDERATIONS .....	35
II.	THE SUBSTRUCTURE .....	38
A.	Foundations - basic rules .....	38
B.	Foundations - design details .....	39
C.	Base courses - basic principles .....	43
D.	Base courses - design details .....	44
III.	WALLS .....	47
A.	Walls - basic principles .....	47
B.	Brickwork .....	48
C.	Corners and partitions .....	52
D.	Reinforcements and bondbeams .....	57
IV.	OPENINGS .....	62
A.	Basic principles .....	62
B.	Design details .....	63
C.	Arches .....	67



## Contents (continued)

	<i>Page</i>
V. FLOORS .....	72
A. Ground floors .....	72
B. Floors above ground level .....	74
VI. ROOFS, VAULTS AND DOMES .....	82
A. Flat roofs .....	82
B. Pitched roofs .....	84
C. Vaults .....	92
D. Domes .....	97
VII. FIREPLACES AND SERVICES .....	101
A. Fireplaces .....	101
B. Services .....	102
<b>PART THREE</b>	
<b>SURFACE PROTECTION</b> .....	104
I. BASIC CONSIDERATIONS .....	104
A. The need to protect .....	104
B. Functions and requirements .....	106
C. Deficiencies in earth walls .....	106
D. Good practice .....	109
II. SURFACE PROTECTION .....	113
A. Types of surface protection .....	113
B. Renderings .....	117
C. Earth renderings .....	121
D. Paints and sealers .....	124
E. Whitewashes .....	127
F. Slurries .....	131
III. DETAILED ASPECTS OF SURFACE PROTECTION .....	134
A. Lathing and anchoring .....	134
B. Finishes and decorations .....	139
IV. TESTS ON RENDERINGS .....	140
A. Small-scale tests .....	140
B. Large-scale tests .....	141
C. Building or building panels .....	143

## Contents (continued)

	<i>Page</i>
<b>PART FOUR</b>	
<b>PRODUCTION OF COMPONENTS</b> .....	144
INTRODUCTION .....	144
I. THE PRODUCTION OF RAMMED EARTH .....	145
A. Preparation of the soil .....	145
B. Formwork .....	146
II. PRODUCTION OF ADOBE BLOCKS .....	155
A. Preparation of the soil .....	155
B. Manual production .....	158
C. Mechanized production .....	160
III. PRODUCTION OF COMPRESSED BLOCKS .....	162
A. Pulverization .....	162
B. Screening and mixing .....	164
C. Types of presses .....	167
<b>PART FIVE</b>	
<b>BIBLIOGRAPHY</b> .....	182







# **PART ONE**

## **BASIC PRINCIPLES OF EARTH APPLICATION**

### **INTRODUCTION**

Immense experience has been acquired on building in earth in recent times. It is, however, far from being complete. The criteria for the suitability of a soil currently in use are far from final and should not be too literally interpreted.

The majority of design charts used have been borrowed from road engineering techniques and these are fairly suitable for earth construction. Many suitability criteria, however, were drawn up on a regional scale and are, therefore, not always universal in application. The best course is to draw on their general approach while adapting them to local conditions. They should be used primarily for their qualitative information.

Interpretation should be as flexible as possible, as should be their amendment, taking into account the ranges of values which can to some extent be enlarged and still provide good results. Even so, only experienced personnel who can appreciate the consequences of their use should be allowed to interpret suitability criteria. In stabilization, for example, it is possible to depart to some extent from the ideal conditions described by the suitability criteria, but at the same time the dangers involved in doing so must be appreciated. When a well-defined soil is used regularly, experience and know-how will confirm the accuracy of the values considered (e.g., proportions). It should, however, never be forgotten that the economy of the final product depends basically on choosing a new soil. For large-scale projects, preliminary comparative tests can be carried out on test walls built using different methods and so make it possible to find the most suitable solution. Apart from these, indicator and laboratory (if necessary) tests are essential if the greatest efficiency is to be obtained.

Similarly the suggested suitability criteria must be regarded as a starting point. They cannot be considered as binding recommendations and even less as standards.



# I. FUNDAMENTALS OF SOIL SCIENCE

## A. Basic properties of soil

### 1. Texture

Also referred to as the grain size distribution of a soil, texture represents the percentage content of the different grain sizes. This texture of a soil is determined by the sieving of the rougher grains: pebbles, gravel, sands and silts, and by sedimentation for the fine clayey materials. The classification of grain sizes adopted by a large number of laboratories based on the ASTM-AFNOR standards are as follows:

V	:	Pebbles	:	200 mm	-	20 mm
V	:	Gravel	:	20 mm	-	2 mm
IV	:	Coarse sand	:	2 mm	-	0.2 mm
III	:	Fine sand	:	0.2 mm	-	0.06 mm
II	:	Silts	:	0.06 mm	-	0.002 mm
I	:	Clays	:	0.002 mm	-	0 mm

### 2. Plasticity

Plasticity refers to the property of a soil causing deformation without elastic failure characterized by cracking or disintegration. The plasticity of a soil, as well as the limits between differing states of consistency, is determined by making measurements carried out on the "fine mortar" size of the soil (diameter of grains 0.4 mm). The quantity of water, expressed as a percentage, which corresponds to the limit of the transition between the state of fluid consistency and the state of plastic consistency, is called the liquid limit (LL). The transition between plastic and the solid state is called the plastic limit (PL). At LL the soil starts to manifest a certain resistance to shearing. At PL the soil stops being plastic and becomes brittle. The plasticity index (PI), equal to LL - PL, determines the range of plastic behaviour of the soil. The higher the PI, the higher is the clay content of the soil. The combination of the LL and the PL specifies the sensitivity of the soil to variations in humidity.

### 3. Compactability

The compactability of a soil defines its ability to be compacted to a maximum for a given compacting energy and degree of humidity (optimal moisture content - OMC). When a volume of soil is subjected to the action of a force, the material is compressed and the voids ratio decreases. As the density of a soil is increased its porosity is reduced, and less water can penetrate it. This property is the result of the interpenetration of the grains, which in turn results in a reduction of the disturbance of the structure caused by water action. The compactability of a soil is measured by the Proctor compaction test. The compactability

of a soil can be represented on a compactibility diagram where OMC is plotted against optimal dry density for any given compression energy.

#### *4. Cohesion*

The cohesion of a soil is an expression of the capacity of its grains to remain together when a tensile stress is imposed on the adhesive or cementitious properties of its coarse mortar (grain size of 2 mm diameter) which binds the inert grains together. This property thus contributes to the quantity and adhesive quality of the clays. The coarse mortars may be grouped as follows:

- (a) Sandy mortar;
- (b) Lean mortar;
- (c) Average mortar;
- (d) Fat mortar;
- (e) Clays.

Cohesion is measured by a tensile test in the moist condition sometimes also referred to as the "8" test. Cohesion is plotted in a tensile strength chart.

### *B. Composition of solids in soil*

#### *1. Pebbles*

Pebbles range in size from 20 to 200 mm. They form a rough material which is the result of the disintegration of the parent rock from which they draw their basic characteristics. They may also have been carried from elsewhere. Young pebbles still have sharp corners. Severely weathered pebbles are rounded, as are those which have been carried by watercourses or glaciers.

#### *2. Gravel*

Gravel ranges in size from 2 to 20 mm. It is made up of small grains of rough material, which are the result of the disintegration of the parent rock and pebbles. It may also have been carried by water courses and thus be rounded, though angular gravel also exists. Gravel constitutes the skeleton of the soil and imposes a limit to its capillarity and shrinkage.

#### *3. Sands*

Sand ranges in size from 0.06 to 2 mm. It is often made up of particles of silica or quartz. Some beach sand contains calcium carbonate (shell fragments). The sandy component of a soil is marked by its high internal friction. Sand grains lack cohesion because of the weak effect of films of water close to their surfaces. The low adsorption of these surfaces limits swell and shrinkage. The open structure and permeability are typical of sand.

#### *4. Silt*

The grain size of silt ranges from 0.002 ( $2\mu$ ) to 0.06mm. From the physical and chemical point of view the silt component is identical to the sand component, the only difference being one of size. Silt gives soil stability by increasing its internal friction. The films of water between the particles grant a certain degree of cohesion to silty soil. Because of their high degree of permeability silty soils are very sensitive to frost. They are subject to small-scale swell and shrinkage.

#### *5. Clays*

Clay grains are smaller than  $2\mu$ . They differ from other grains in their chemical composition and physical properties. In chemical terms they are hydrated aluminosilicates formed by the leaching process acting on the primary minerals in rock. Physically speaking, clays often assume a platy elongated shape. Their specific surface is infinitely greater than that of rougher round or angular particles. Clays are very susceptible to swell and shrink.

#### *6. Colloids*

Sandy material is often coated with a sort of gluey paste which sticks it into aggregate. This gluey paste is made up of "colloids", the dimensions of which are less than  $2\mu$ . Some of these are the result of the weathering of the parent rock. These are mineral colloids, the chief of which is clay. Clay is not the only mineral colloid. It is often mixed with very fine quartz debris, with hydrated silica, extremely fine crystals of limestone and magnesium colloids, as well as colloidal iron and aluminium oxides. Other colloids result from the decomposition of organic matter. These are the organic colloids: humus and bacterial glues.

### *C. Soil identification*

#### *1. Sampling*

##### *(a) Collecting samples*

A manual auger or a mechanical version mounted on a lorry can be used. Augers allow rapid sampling to considerable depths. With extensions, depths of between 5 and 6 metres can be reached (compared with depths of between 0.60 and 0.70 m without extensions). Normal sizes for augers range from 6 to 25 cm. They weigh about 5 kg, increasing by 3 kg with every 1 m extension. The main drawback of the tool is the risk of mixing surface layers with those at a greater depth.

An alternative is to dig a hole with a side of 1 m to a depth of 2 m. The hole should be properly oriented with respect to the sun in order to facilitate observation. Precautions must be taken to ensure the safety of the labourers, as there is a cave-in risk when working in poorly



cohesive material. The excavated earth is removed in its entirety and no samples are taken from it. The soil used in the analysis is taken from one of the sides of the hole by digging sideways into the wall. Samples can also be taken from natural slopes where the dip of the soil layers is clearly visible. Care should be taken to remove all the vegetation and organic matter from the surface.

#### *(b) Sample weight*

In principle, 1.5 kg of soil is enough for all basic identification tests, except for compactibility tests, which require 6 to 10 kg. If one brick measuring 29.5 x 14 x 9 cm is to be tested, 10 kg of soil is required. The quantity of soil to be taken for the sample will depend on the number and type of tests to be carried out, on the degree of precision required (as this may make a double test series necessary), on the expenses and difficulties involved (as the cost of a test is often related to the quality of the soil under test), and finally on grain size, as a large-grain soil requires a larger sample than a fine soil.

#### *(c) Sample quality*

The sample must be representative of the quality of the soil under test. In order to ensure that the sample is representative, an effort must be made to ensure that the following principles are observed.

- Care must be taken to avoid soil contamination due to the mixing of different sampling horizons;
- Take nothing from and add nothing to the sample. Do not try to improve its natural state;
- Take samples from only a very restricted area;
- If the soil is heterogeneous, do not try to take an average but take more samples from each different spot;
- In order to divide a sample up, place it in the shape of a cone on a clean tissue; flatten it and divide it into four. Discard two of the opposing sectors, then shape the material into a cone again and repeat the operation until the desired quantity is obtained.

## *2. Preliminary tests*

Fieldwork requires a number of rapid identification tests to help in determining what soils are likely to be suitable for construction purposes. These simple field tests make it possible to evaluate some of the properties of the material and to determine the suitability of the soil for construction purposes. These tests are somewhat empirical, and they should be repeated to ensure that more than a superficial impression is gained. From these tests it can be seen whether further laboratory testing is justified.

#### *(a) Visual examination*

The dry soil is examined with the naked eye to estimate the relative proportions of the sandy and fines fractions. Large stones, gravel, and

coarse sand are removed in order to facilitate evaluation (this operation must also be carried out for all the following tests). The fines fraction is made up of grain sizes with a diameter of less than 0.08 mm. This diameter lies at the limit of the resolving power of the human eye.

(b) *Smell test*

The soil should be smelt immediately after removal. If it smells musty it contains organic matter. This smell will become stronger if the soil is heated or wetted.

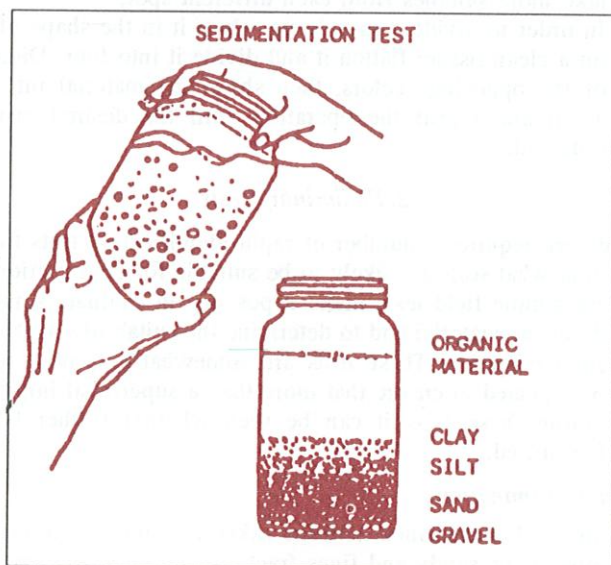
(c) *Nibble test*

Care should be taken that it is safe to place any samples in the mouth. The tester nibbles a pinch of soil, crushing it lightly between the teeth. The soil is sandy if it grinds between the teeth with a disagreeable sensation. Silty soil can be ground between the teeth but without giving a disagreeable sensation. Clayey soil gives a smooth or floury sensation, and a small piece of it is sticky when applied to the tongue.

(d) *Touch test*

After removing the largest grains, crumble the soil by rubbing the sample between the fingers and the palm of the hand. The soil is sandy if a rough sensation is felt and if it has no cohesion when moist. The soil is silty if it gives a slightly rough sensation and is moderately cohesive when moistened. The soil is clayey if when dry it contains lumps or concretions which resist crushing, and if it becomes plastic and sticky when it is moistened.

(e) *Sedimentation test*



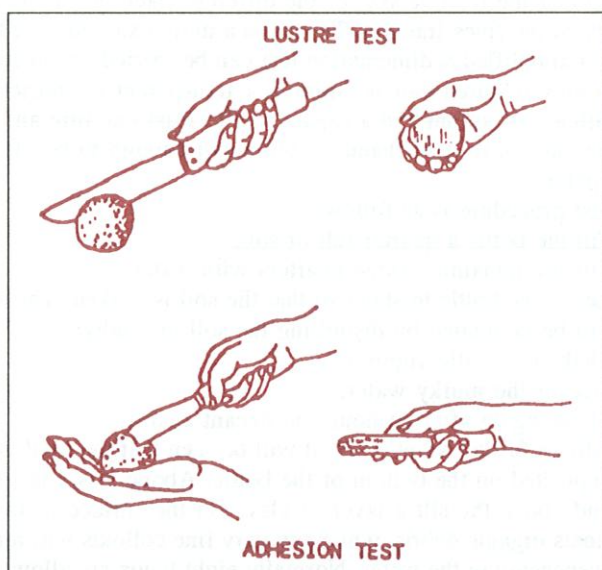
The foregoing tests make it possible to form an idea of the texture of the soil and the relative size of the different fractions, as well as of the quality of the fines fraction. To obtain a more exact idea of the soil fractions, a simplified sedimentation test can be carried out in the field. The apparatus required can be simple: a transparent cylindrical glass bottle, with a flat bottom and a capacity of at least one litre and with a neck wide enough to get a hand in, but small enough to be closed off with the palm.

The test procedure is as follows:

- Fill the bottle a quarter full of soil;
- Fill the remaining three quarters with water;
- Leave the bottle to stand so that the soil is soaked. The soaking can be facilitated by disturbing the soil manually;
- Shake the bottle vigorously;
- Decant the murky water;
- Shake again after an hour and decant again;
- After a further 45 minutes, it will be seen that the sand has been deposited on the bottom of the bottle. Above it is a layer of silt and above the silt a layer of clay. On the surface of the water floats organic debris, while any very fine colloids will remain in suspension in the water. Normally eight hours are allowed to go by before measuring the different layers precipitated. First of all measure the overall depth of the sediment (100 per cent), without including the depth of clear water covering it, and then measure each separate layer.

This measurement of the respective depths of the sediment, which makes it possible to estimate the percentage of each grain fraction, is slightly distorted by the fact that the silt and clay fractions will have expanded and are thus slightly larger than they really are.

(f) *Lustre test*



A slightly moist ball of earth is cut in two with a knife. If the freshly revealed surface is dull, the soil will be predominantly silty. A shiny surface, on the other hand, indicates the presence of a plastic clayey soil.

(g) *Adhesion test*

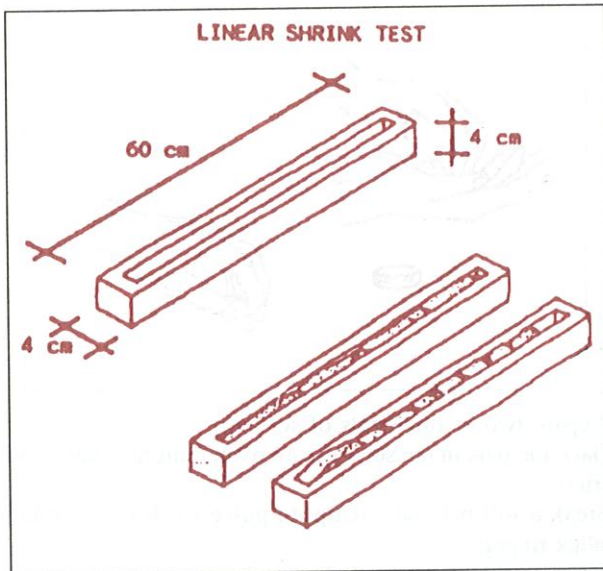
Take a mass of moist soil which does not stick to the fingers and insert a spatula or knife into it. The soil is extremely clayey, if the spatula penetrates it with difficulty, and soil sticks to it upon withdrawal. The soil is moderately clayey, if the spatula can be pushed into it without great difficulty and soil sticks to it upon withdrawal. The soil contains only a little clay if the spatula can be pushed into it without encountering any resistance at all, even if the spatula is dirty upon withdrawal.

(h) *Washing test*

Wash the hands with the slightly moistened soil. The soil is sandy if the hands easily rinse clean. The soil is silty if it appears to be powdery and the hands can be rinsed clean without too much difficulty. The soil is clayey if it gives a clayey sensation and the hands can be rinsed clean only with difficulty.



(i) *Linear shrinkage test*

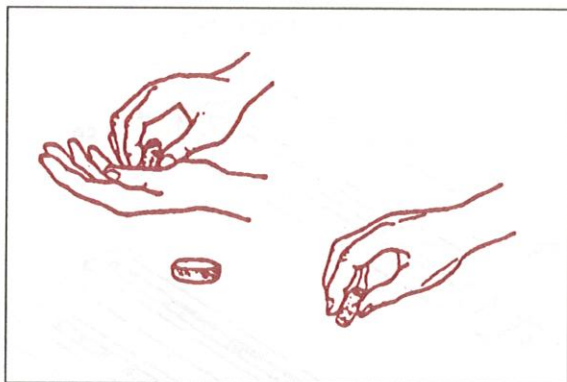


The linear shrinkage test, or Alcock's test, is performed with the help of a wooden box, 60 cm long, 4 cm wide and 4 cm deep. The inside surfaces of the box are greased before being filled with moist soil with an OMC. The soil is pressed into the corners of the box with a small wooden spatula which is also used to smooth the surface. The filled box is exposed to the sun for a period of three days, or left in the shade for seven days. After this period the hardened and dried mass of soil is pushed to one end of the box and the total shrinkage of the soil is measured from the soil to the other end of the box.

### 3. *Visual analysis of fines*

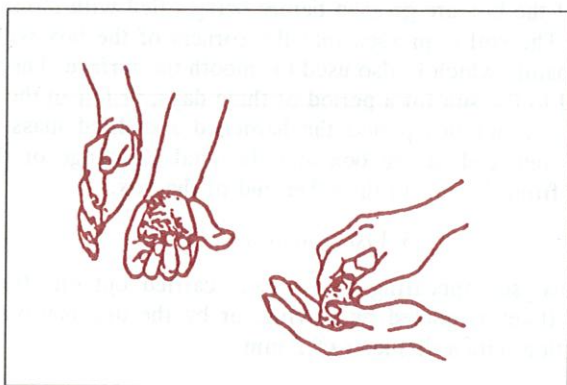
The analyses appearing below were carried out on "fine mortar" (diameter 0.4mm) graded by sieving, or by the decantation test on a grain fraction with a diameter of 2 mm.

(a) *Dry strength test*



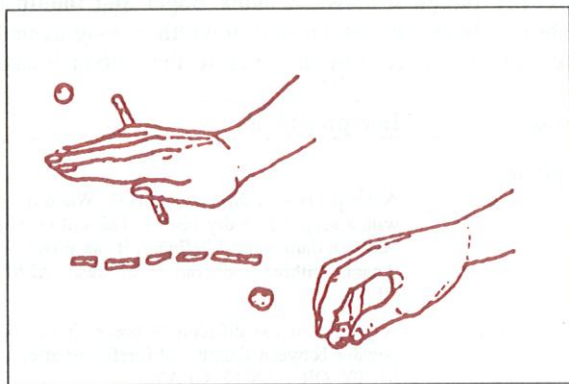
- Prepare two or three pats of soft soil;
- Place the pats in the sun or in an oven until they have completely dried;
- Break a soil pat and attempt to pulverize it between thumb and index finger;
- Estimate the strength of the pat.

(b) *Water retention test*



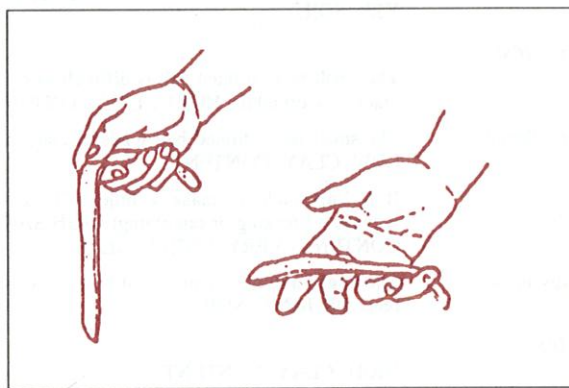
- Prepare a ball of "fine mortar" 2 or 3 cm in diameter;
- Moisten the ball so that it sticks together but does not stick to the fingers;
- Slightly flatten the ball and hold it in the palm of the extended hand. Vigorously hit the palm of the hand holding the ball so that the water runs out. The appearance of the ball may be smooth, shiny or greasy;
- Next press the ball flat between index finger and thumb and observe the reaction.

(c) *Consistency test*



- Prepare a ball of "fine mortar" 2 or 3 cm in diameter;
- Moisten the ball so that it can be modelled without being sticky;
- Roll the ball on a flat clean surface until a thread is slowly formed;
- If the thread breaks before its diameter is reduced to 3 mm, the soil is too dry;
- Add water;
- The thread should break when its diameter is 3 mm;
- When the thread breaks, make it into a small ball again and crush it between and index finger.

(d) *Cohesion test*



- Make a roll of soil about the size of a sausage with a diameter of 12 mm;
- The soil should not be sticky and should be capable of being shaped so that it makes a continuous thread 3 mm in diameter;

- Place the thread in the palm of the hand. Starting at one end carefully flatten it between index finger and thumb to form a ribbon of between 3 and 6 mm in width as long as possible;
- Measure the length obtained before the ribbon breaks.

Observations	Interpretations
<i>Dry strength test:</i>	
High dry strength	A dry pat is very difficult to break. When it does, it breaks with a snap, like a dry biscuit. The soil cannot be crushed between thumb and forefinger, it can merely be crumbled, though without reducing it to dust: ALMOST PURE CLAY.
Moderate dry strength	A pat is not too difficult to break. It can be crushed to powder between thumb and forefinger after a little effort: SILTY OR SANDY CLAY.
Low dry strength	A pat can be easily broken and can be reduced to powder between thumb and forefinger without any difficulty at all: SILT OR FINE SAND, LOW CLAY CONTENT.
<i>Water retention test:</i>	
Rapid reaction	5 or 6 blows are enough to bring the water to the surface. When pressed the water disappears and the ball crumbles: VERY FINE SAND OR COARSE SILT.
Slow reaction	20 to 30 blows are needed to bring the water to the surface. When pressed the ball does not show any cracking nor does it crumble; it flattens: SLIGHTLY PLASTIC SILT OR SILTY CLAY.
Very slow reaction	No water appears on the surface.
or no reaction at all	When pressed the ball retains its shiny appearance: CLAYEY SOIL.
<i>Consistency test:</i>	
Hard thread	The small reconstituted ball is difficult to crush, does not crack nor crumble: HIGH CLAY CONTENT.
Medium hard thread	The small reconstituted ball tends to crack and crumble: LOW CLAY CONTENT.
Fragile thread	It is impossible to make a little ball from the thread without it breaking or crumbling: HIGH SAND OR SILT CONTENT, VERY LITTLE CLAY.
Soft or spongy thread	The thread and the reconstituted ball has a soft or spongy feel: ORGANIC SOIL.
<i>Cohesion test:</i>	
Long ribbon (25 to 30 cm)	HIGH CLAY CONTENT.
Short ribbon (5 to 10 cm obtained with difficulty)	LOW CLAY CONTENT.
No ribbon at all	VERY LOW CLAY CONTENT.



### *D. Suitability of soils for stabilization*

Soil	Shrinkage and swelling	Sensitivity to frost action	Bulk density at OMC (kg/m <sup>3</sup> )	Voids ratio (vs = 2700 kg/cm <sup>3</sup> )	Compressive strength dry	General suitability (without stabilization)
GW	Clean gravel	Almost none	2000	0.35		Not suitable. Fine soil should be added.
GP	Well graded	Almost none	1840	0.45		Not suitable. Fine soil should be added.
GM	Poorly graded	Almost none	1760	0.50		Suitable, but lacks cohesion. Erodes easily. Add fine soil.
GC	Silty gravel	Slight to medium	1920	0.40		Suitable. Sometimes fine soils should be added.
SW	Clayey gravel	Slight to medium	1920	0.40		Not suitable. Fine soil should be added.
SP	Clean sand	Almost none	1600	0.70		Not suitable. Fine soil should be added.
SM	Poorly graded	Almost none	1600	0.70		Suitable, but lacks cohesion. Erodes easily. Add fine soil.
SC	Silty sand	Slight to high	1700	0.60		Suitable. Sometimes fine soils should be added.
CL	Clayey sand	Slight to high	1520	0.80	Slight to high	Sometimes suitable. Sandy soil should be added.
ML	Low-plasticity clay	Medium to high	1600	0.70	Very slight	Suitable, but lacks cohesion. Erodes easily. Add fine soil.
OL	Low-plasticity silt	Medium to very high	1440	0.90		Suitable. Sometimes fine soils should be added.
CH	Organic silt and clays with low plasticity	Medium to high	1440	0.90		Suitable, but lacks eventual cohesion.
MH	Highly plastic clay	High	1440	0.90		Not suitable. Sometimes acceptable.
OH	Highly plastic silt	Very slight	1600	0.70	Medium to very high	Rarely suitable. Sandy soil should be added.
	Highly plastic	Medium to high	1600	0.70	Very slight to medium	Very rarely suitable.
	Highly plastic organic	Very high	1600	0.70	Medium to high	Not suitable.

## II. PRINCIPLES OF SOIL STABILIZATION

### *A. Basic considerations*

#### *1. Fundamental problem*

Building in soil implies a choice between three main approaches:

- Using the soil available on the site and adapting the project as far as possible to the quality of the soil;
- Using another soil more suited to the requirements of the project but which has to be brought to the site;
- Modifying the local soil so that it is better suited to the requirements of the project.

The third possibility is generally referred to as "soil stabilization" and comprises the entirety of techniques permitting the improvement of the properties of the soil.

#### *2. Definition*

Stabilizing a soil implies the modification of the properties of a soil-water-air system in order to obtain lasting properties which are compatible with a particular application. Stabilization is nevertheless a complex problem, as an extremely large number of parameters are involved. In fact a knowledge of the following is necessary:

- The properties of the soil requiring stabilization;
- The planned improvements;
- Project economy: costs and delays involved in soil stabilization;
- The soil construction techniques chosen for the project and the system of construction;
- Maintenance of the completed project; maintenance cost.

The improvement of the properties of the soil by stabilization will be successful if the procedure used is compatible with the imperatives of the programme - in particular the cost of and delays in construction, and the cost of maintenance.

#### *3. Objectives*

Action can be directed at only two characteristics of the soil itself, i.e., its texture and structure. There are three courses of action:

- Reducing the volume of interstitial voids: acts on porosity;
- Filling the voids which cannot be eliminated: acts on permeability;
- Improvement of the bonding between grains; acts on mechanical strength.

The main objects aimed at are:

- Achieving better mechanical characteristics: improving dry and wet compressive strength, tensile strength and shearing strength;
- Achieving better cohesion;

- Reducing porosity and changes in volume: shrink and swell due to water;
- Improvement of resistance to wind and rain erosion: reduction of surface abrasion and water-proofing.

#### 4. Procedures

There are three basic stabilization procedures:

(a) *Mechanical stabilization*: This is the compaction of the soil resulting in changes in its density, mechanical strength, compressibility, permeability and porosity.

(b) *Physical stabilization*: Here the properties of the soil can be modified by acting on its texture: e.g., the controlled mixing of different grain fractions. Other techniques can involve heat treatment, drying or freezing, electrical treatment, electro-osmosis to improve the draining qualities of the soil, and giving new structural qualities.

(c) *Chemical stabilization*: In this procedure other materials or chemicals are added to the soil, thus modifying its properties either by a physico-chemical reaction between the grains and the materials or the added product, or by creating a matrix which binds or coats the grains. A physico-chemical reaction can lead to the formation of a new material: for example, a pozzolana resulting from a reaction between clay and lime.

#### 5. When is stabilization required

Stabilization is not compulsory. It can be ignored quite satisfactorily and the soil can be used for construction without stabilizing.

Nevertheless, there is clearly a tendency at present towards the over use of stabilization, which is regarded as a universal panacea for all problems. This attitude is unfortunate as stabilization can involve considerable extra costs, ranging from 30 to 50 per cent of the final cost of the materials. Furthermore stabilization complicates the production of the material, e.g., through longer preliminary studies of the behaviour of the material.

It is thus advisable to insist that stabilization be used only when absolutely essential and that it should be avoided where economic resources are limited.

- Do not stabilize when the material is not exposed to water: (i.e., sheltered walls, dressed walls, inside walls, architecture designed to accommodate the exigencies of soil as a building material).
- Stabilize when the material is very exposed: (i.e., when there is poorly designed architecture which ignores the rules of building with earth; or requirements imposed by the site, such as a damp site, walls exposed to driving rain, and so on. However, there may be other reasons for stabilizing the material such as:



- The improvement of the soil's compressive strength;
- Raising the material's bulk density, or even reducing it.

## *B. Methods of stabilization*

### *1. Densification*

There are two different ways in which density can be increased:

(a) Either by mechanically manipulating the soil, so that a maximum of air can be eliminated; by kneading and compressing the soil. Grain size distribution is not affected, but grain structure is changed because the grains are redistributed. The soil is not simply compressed in its original state. It is first ground to make it more uniform, and then compressed. After the grinding phase, it is possible - but not indispensable - to make use of dispersants or waxes which may facilitate compaction.

(b) By filling the voids as far as possible with other grains. If this second method is to be used, grain size distribution must be perfect: the voids left between each group of grains is filled by another group of grains. This method acts directly on grain size distribution.

### *2. Reinforcement*

If there are reasons for not acting on the grain size distribution of the soil and if the material remains overly sensitive to movements induced by various causes such as compression, tension, water action and thermal expansion, among others, these movements can be counteracted with a reinforcement. This can be made of a wide variety of fibres: animal, vegetable, mineral or synthetic. The fibre reinforcement has its effect at the macroscopic level, that is to say at the level of grain aggregations rather than at the level of the individual grains.

### *3. Construction*

A three-dimensional matrix can be introduced in the soil. Strong and inert, it resists all movements of the soil. This is in essence the consolidating action of cementing. It results in the filling of the voids with an insoluble binder which coats the grains and holds them in an inert matrix. The main stabilizer which acts by this mechanism is Portland cement. Similar results can be achieved with electrolytic solutions of sodium silicate salts or with certain resins and adhesives.

Viewed as a chemical reaction, the essential characteristic of this stabilization mechanism is that the formation of the inert matrix is relatively independent of the clay. In fact, the main consolidating reactions take place in the stabilizer itself and between the stabilizer and the sandy fraction of the soil. Even so, secondary reaction between the stabilizer and the clayey fraction may be observed. The quantity and



quality of the clay has an effect on the efficiency of the stabilization procedure and may alter the mechanical behaviour of the material.

#### *4. Linkage*

In this case the inert matrix introduced in the soil includes the clays. Two mechanisms are known and they give the same result.

(a) An inert matrix is created by the clays: use is made of the negative and positive charges of the clay plates or their chemical composition to bind them together by means of a stabilizer, which plays the role of binder or catalyst for this bond. Certain chemical stabilizers act in this way, including certain acids, polymers, flocculants etc.

(b) An inert matrix is formed by the clay. A stabilizer reacts with the clay and precipitates a new inert and insoluble material, which is a sort of cement. This is the pozzolana reaction and is obtained primarily with lime. The reaction proceeds slowly and depends essentially on the quantity and quality of the clay.

#### *5. Imperviousness*

This stabilization method helps to reduce water erosion, swell, and shrinkage when the material is subjected to successive wetting and drying cycles. There are two possible waterproofing methods:

(a) All the voids, pores, cracks and microcracks are filled with a material which is unaffected by water. Bitumen is one of the best examples of a product which acts in this way. This stabilization method is particularly suitable for sandy soils with a good stability for their volume and which are not much affected by the movement of water. It is equally suitable for silty and clayey soils which need larger amounts of stabilizer because of their greater specific surface.

(b) A material is dispersed in the soil which expands upon the slightest contact with water and prevents the infiltration of pores. A typical material of this type is bentonite.

#### *6. Waterproofing*

Here the object of the procedure is the movement of water and water vapour in the soil. This can be achieved either by changing the nature of this water, or by reducing the sensitivity of the clay plates to water.

Three systems are used:

(a) The modification of the state of the pore water: drying the soil by introducing calcium chloride into it. This raises surface tension, reduces the vapour pressure of the water and the evaporation rate, and also reduces variation in moisture content.

(b) Ion exchange: ions are replaced by others until the ions are very well fixed to the clay plates and the water can no longer dilute them. Certain acids can give rise to this phenomenon.

(c) Molecules are fixed on one of the extremities of the clay plates on the outside of compact aggregates. The other ends of these molecules are water repellent. Certain quaternary amines and resins work in this way.

### *C. Suitability of soils for stabilization*

#### *1. Soils suitable for fibres and mineral aggregates*

These criteria for fibre-stabilized or mineral-stabilized soils are accompanied by the maximum compression rates to which the materials may be subjected and at which they can be used in all safety. It may thus be observed that fibre-stabilized soils should not be worked with at above  $3 \text{ daN/cm}^2$  and that mineral-stabilized soils have a limit of  $5 \text{ daN/cm}^2$ . These are the maximum compression rates. Certain soils may not be able to achieve these rates. Thus the values given by the performance curve should not be interpreted as permissible values but as values which should in no case be exceeded.

Usage criteria applicable to soil stabilized with fibre and minerals exist. These were drawn up in the 1940s as the result of prolonged laboratory research on a very large number of samples. These laboratory observations were subsequently enriched by a mass of practical construction experience. Since then these criteria have been successfully applied to thousands of projects. Nevertheless, these criteria were established in northern Europe, and are above all applicable to the soils of that region, which are of a loess-based silt sort. It is possible that these criteria can be adopted to other soil types, but only after extensive verification.

#### *2. Soils suitable for cement*

Nearly all soils, except those which have an excessive content of organic material, can be treated with cement and thus undergo a drastic improvement in their properties. Salt-rich soils are also difficult to stabilize with cement; even so, an increase in the proportion of cement can often bring good results. Soils which have a large clay fraction mix only with difficulty and require large quantities of cement. When the mixing process is very closely controlled under laboratory conditions good results can be achieved with clayey soils. In practice, however, cement is not used for stabilizing clay when the liquid limit is higher than 30 per cent. Preliminary treatment of these extremely clayey soils with hydrated lime may improve the likelihood of obtaining good results with cement added at a later date. Numerous tests give indications regarding the suitability and proportion of cement.

- *Abrasion test:* the proportion of cement should reduce loose material to 3 per cent after 50 cycles, which is an excellent performance.



- *Erosion test*: the proportion of cement should reduce the mean depth of holes to 15 mm - an excellent performance for this extremely severe test.
- *Wetting-drying*: an optimum proportion should reduce material losses to 10 per cent - an excellent performance for this extremely severe test.
- *Freeze-thaw*: an optimum proportion should reduce material losses to 10 per cent: an excellent performance for this excessively severe test.
- *Shrinkage* (based on the Alcock test):

Linear shrinkage (mm)	Cement	:	soil (vol.)
Less than 15	1	:	18
From 1-5 to 30	1	:	16
From 30 to 45	1	:	14
From 45 to 60	1	:	12

These values are applicable to soils compressed to a maximum of 40 dAN/cm<sup>2</sup>. The quantity of cement can be reduced to less than 30 per cent for soils compressed to 100 daN/cm<sup>2</sup>.

- *Organic matter*:

When the pH value is greater than 7 (alkaline or basic): calcareous soils, brown alkaline soils, and some grey soils can be stabilized with 10 per cent cement: rates of between 1 and 2 per cent of organic matter are in general not a problem.

When the pH value is less than 7 (acid): grey soils can be successfully stabilized with 10 per cent cement if the content of organic matter is less than 1 per cent. Acidic brown soils can sometimes be stabilized with success if they contain less than 1 per cent of organic matter. If anomalies are found to exist, preliminary treatment with calcium chloride (1 to 2 per cent) may bring about a certain improvement.

### 3. Soils suitable for lime

Lime has only a very limited effect on soils with a high organic matter content (content higher than 20 per cent) and on soils short of clay. It is more effective and can be more effective than cement on clay-sand soils and especially on very clayey soils. The effects of lime are thus highly dependent on the nature of the soils involved, but a comparison with the effects of cement can, in many cases, be attempted. It has been observed that lime reacts far more quickly with montmorillonite clays than with the kaolinites, reducing the plasticity of the montmorillonites and having only a slight effect on the plasticity of the kaolinites. Water content has a significant effect on clay soils which can be stabilized with lime, particularly in the pulverization and compaction stage. Natural pozzolanas react particularly well with lime.

For the rest it may be noted that the proportions of lime quoted are for industrial-quality lime containing between 90 and 99 per cent of quicklime. For lime produced by less sophisticated methods, which may

contain only 60 per cent of quicklime (the rest being made up of unfired or over-fired components), the proportion must be increased. The two main methods of improving the performance of soil with lime may be summarized as follows:

(a) *Modification of the soil*: the lime is added until a setting point is reached. This operation reduces the plasticity of the soil and improves its flocculation.

(b) *Soil stability*: the proportions are much higher. Reference monographs on the suitability of soils and the proportion of lime must be interpreted with a great deal of reserve.

Tests should be carried out only after allowing a curing period of three months.

- *Abrasion test*: the proportion of lime should reduce material loss to 3 per cent after 50 cycles - an excellent performance.
- *Erosion test*: the proportion of lime should reduce the mean depth of holes to 15 mm - an excellent performance for this extremely severe test.
- *Wetting-drying*: the proportion should reduce material losses to 10 per cent - an excellent performance for this extremely severe test.
- *Freeze-thaw*: the proportion of lime should reduce material losses to 10 per cent - an excellent performance for this excessively severe test.
- *Compression strength*: the reactivity of soils containing lime was determined by Thompson in 1964. The soils are stabilized with the optimum proportion of lime; the increase in compression strength after curing for seven days at 23° C is defined as the reactivity of the soil with the lime:

Group	Increase	Reactivity
1	1	Non-reactive
2	1 to 3.5	Non-reactive
3	3.5 to 7	Reactive
4	7 to 10.5	Reactive
5	10.5 and more	Reactive

This makes it possible to decide quickly if further testing is justified.

#### *4. Soils suitable for bitumen*

Although clayey soils have been successfully treated with cutback or hydrocarbon emulsions, stabilization with hydrocarbons is more suitable for sandy soils or sandy-gravel soils, for soils lacking in cohesion or when an impermeable finish is particularly desired. With extremely clean sandy soils, the low adhesion of the bitumen to the surface of the siliceous particles can lead to the separation of the bitumen under



the action of water, with the result that the stabilizing effect of the bitumen on the soil is considerably reduced. Moist soils are in general not suitable for bitumen stabilization, because of the difficulty of mixing the hydrocarbon with the soil.

- *Soluble salts*: their presence in a soil is likely to lead to the deterioration of the soil as a result of the successive hydration and dehydration of the soil. Salts also have a tendency to cause efflorescence. Furthermore, in the presence of a stabilizer such as bitumen, they can be very harmful to the binding films between the bitumen and the clays. The presence of salts in a soil which can be stabilized with a bitumen should preferably not exceed 0.25 per cent.
- *Proportioning*: the IIHT (California, United States) makes recommendations for adobe which involves carrying out tests by progressively increasing the bitumen content as follows (in percentage terms):

Cutback: 2, 3, 4, 5

Emulsion: 3, 4, 5, 6

Each test is carried out on three or four samples which are tested for compression and bending strength, and for erosion resistance until satisfactory results are obtained. IIHT also points out that excessively clayey soils requiring more than 5 per cent of cutback or 6 per cent of emulsion are not suitable for making adobes because of their marked shrinkage.

For emulsions the following figures may be given:

High sand content soils : 4 to 6 per cent

Low sand content soils : 7 to 12 per cent

Clayey soils : 13 to 20 per cent

The percentage is for the hydrocarbon itself and not for the suspending liquid.

### III. CHARACTERISTICS OF SOIL STABILIZERS

#### *A. Fibre*

Stabilization by means of fibre reinforcement, very often straw, is widely used. Straw should, in fact, be regarded as a structural reinforcement agent, similar to gravel. Nowadays, even in the most modern and industrial settings, such as in adobe production in the United States of America, straw combined with bitumen is often added to the soil. This method of stabilization is interesting because it can be adapted to various methods of execution, with soil used in the liquid or plastic state, or even with compaction techniques. Fibres are mainly employed for making kneaded blocks with largely clayey soils, which usually suffer a considerable measure of shrinkage. Craft production of straw-stabilized adobe brick varies greatly. Quite apart from this, straw is also used for daub, clay-straw, cob, as well as compressed blocks and rammed earth.

Fibres hinder cracking upon drying by distributing the tension arising from the shrinkage of the clay throughout the bulk of the material. They accelerate drying because they improve the drainage of moisture towards the outer surface through the channels afforded by them. On the other hand, fibres increase absorption in the presence of water. They lighten the material. The volume of straw is often very large, reducing the bulk density and improving its insulating properties. Fibres increase tensile strength. This is undoubtedly their most interesting property.

Earth materials reinforced with fibres can stand up very well to cracking and resist crack propagation. Considered at the level of a potential crack, the fibre opposes the formation of crack in step with the increase in the stress. The degree of shear strength depends largely on the tensile strength of the fibres. Apart from this, good compressive strength can also be achieved with fibre reinforcement, which depends both on the quantity of fibre used and on the initial compressive strength of the soil, the initial tensile strength of the fibres and the internal friction between the fibres and the soil. Some research seems to suggest that preliminary rotting of the straw in the soil for a period of several weeks produces lactic acid which has a secondary effect on the efficiency of the stabilizing action.

With respect to dry compressive strength, the addition of such fibres as straw permits an increase in strength of at least 15 per cent in relation to the material without fibres. In very exceptional cases, the fibres will make hardly any difference at all to the compressive strength, as for example is the case with very sandy material. Fibre-stabilized blocks can withstand high stresses as they absorb a fairly high amount of applied energy. This makes their use particularly attractive in earthquake-prone regions. The addition of fibres makes a fundamental difference to the behaviour of the bricks beyond the failure point. Where non-reinforced



materials crack into bits, reinforced blocks stay in one piece and will continue to increase in compressive strength beyond the failure point of non-reinforced blocks.

The strength of reinforced blocks depends on the quantity of the fibres added, but there is an optimum quantity which should not be exceeded. This is because an overly large quantity reduces density too much, while the number of contact points between the fibre and soil, which are responsible for transmitting stress, becomes too low and the strength of the block is reduced. The minimum proportion for satisfactory results starts at 4 per cent by volume. Quantities of between 20 and 30 kg per m<sup>3</sup> are very common. The straw should by preference be chopped into stalks between 4 and 6 cm long. The best results are obtained when the stalks are scattered in all directions in the soil. Excessively long stalks, in parallel, do not yield good results. Nor are good results obtained when fibres are concentrated in specific spots, or in nests - which may happen when too much fibre is used.

Fibres can also be used together with other stabilizers such as cement, lime, and bitumen. If straw is used with bitumen, the bitumen must be first added to the soil and thoroughly mixed before adding the straw. If the operations are carried out in a different sequence there is a danger that the straw and the bitumen will conglomerate independently of the soil.

The fibres contained in the soil will be preserved without deterioration on condition that the material is kept dry. If the material remains in a moist environment for too long, there is a danger that the fibres will rot. An alternating wetting and drying cycle will not encourage rotting as long as proper drying is certain. Analysis of very ancient material (e.g., adobe from the Egypt of the Pharaohs) has clearly demonstrated this. Fibres may also be attacked by rodents and harmful insects, such as termites, particularly when wet.

The main types of fibres are:

(a) *Plant fibres*: Straw of all kinds: barley, rye, hard and soft wheat, winter barley, lavender; Chaff of cereal crops: wheat, rice, barley etc.; Light fillers such as sawdust and shavings. Other suitable vegetable fibres include hay, hemp, millet, cane trash, coir fibres, sisal, manila, elephant grass, and fibres of bamboo, palm and hibiscus, as well as the left-overs after scutching hemp and flax.

(b) *Animal fibres*: Fur and hair from livestock.

(c) *Synthetic fibres*: Colophane, steel, and glass wool/fibres.

### B. Cement

Hydrated cement reacts in two different ways in soil:

- It may react with itself or with the sandy skeleton. This results respectively in the formation of a pure hydrated cement mortar, or the formation of a conventional mortar.
- It may undergo a three-phase reaction with the clay:

(a) Hydration sets off the formation of cement gels on the surface of the clay aggregations. The lime which comes free during the hydration of the cement tends to react with the clay. The lime is quickly used up and the clay starts to degenerate;

(b) Hydration proceeds and encourages the disaggregation of the clay aggregates. The latter are deeply penetrated by the cement gels;

(c) The cement gels and the clay aggregates become intimately entwined. Hydration continues but more slowly.

In fact three mixed structures are obtained:

- An inert sandy matrix bound with cement;
- A matrix of stabilized clay;
- A matrix of unstabilized soil.

Stabilization does not affect all the aggregate. A stabilized matrix covers the composite aggregations of sand and clay.

The greatest effect is obtained by compression in the moist state. In the plastic state 50 per cent more cement is required to achieve the same effect. The greatest compressive strength is obtained with gravels and sands rather than with silts or clay. For soil, the required quantities of cement depend on its grain size distribution and structure, and the way that it is used. Good results can be obtained with between 6 and 12 per cent. Some soils require only 3 per cent, while the same proportion in others behaves less well than if no cement at all had been used. Generally speaking, at least 6 per cent of cement is required in order to obtain satisfactory results. The compressive strength remains highly dependent on the quantity of cement used. In comparable local conditions and for the same wall thickness (15 cm), a stabilized-earth brick will not necessarily be more economical than a concrete block. A preliminary study of the comparative costs is recommended.

Ordinary Portland cement or cements of the same class are very suitable. There is no point in using high-strength cements, as these produce no particular improvement and are, moreover, very expensive. High-strength cements spoil very easily, making them unsuitable for use on work sites far from the factory. Preference should therefore go to Portland cements of the classes 250 or 350. Cements containing other materials such as slags, fly ash and pozzolanas can also be used, although these cements will only be available close to steel plants and power stations, and similar localities. In contrast, cements with high contents of other materials should not be used because of their sensitivity when curing. These include iron Portland cement, blast-furnace cement, mixed metallurgical cements and slag-clinker cements.

Certain products, added in small quantities to the soil cement during mixing, may improve the characteristics of the finished product.

(a) Some organic products (amine acetate, melamine, aniline) and certain inorganic products (ferrous chloride) reduce the sensitivity of some soils to water.



(b) Lime (2 per cent) can reduce the harmful effects of organic matter, as does calcium chloride (0.3 to 2 per cent), which also speeds setting. The lime also serves to modify the plasticity of the soil and to limit the formation of nodules.

(c) Soda-based additives increase the reactivity of the soil and can induce cementation reactions supplementary to that of the cement with the soil particles. NaOH (sodium hydroxide) can be added in a proportion of 20 to 40 g per litre of the mixing water, while between 0.5 and 1.1 per cent of  $\text{NaSO}_4$  can be added, or 1 per cent of  $\text{Na}_2\text{CO}_3$ ; or 1 per cent  $\text{Na}_2\text{SiO}_2$ .

(d) Between 2 and 4 per cent of bitumen added as emulsion or cutback makes the soil-cement waterproof.

### *Production procedures*

#### *(a) Crushing*

Good cement stabilization demands thorough mixing of the components. The fine elements must not be allowed to form nodules with a size of more than 10 mm. The presence of 50 per cent nodules of 5 mm can cut compressive strength by half.

#### *(b) Mixing*

Good distribution of the cement and the uniformity of the material is provided by mixing. It is important to have a dry soil if the best mixing conditions are to be attained. In wet climates this may make preliminary drying of the soil necessary. Grinding may accelerate drying and help to break up lumps. The water required for the mix should only be added at the very end of the mixing process, after the very necessary dry mixing phase.

#### *(c) Moulding*

The material should be compacted immediately after mixing, before the cement starts to set, and with a controlled moisture content which will be close to OMC. A 4-per cent difference in water content, either more or less, can mean a significant difference in the quality of the material. As a general rule, soil with a high clay content ought to be compacted slightly moister than OMC, while sandy soils should be compacted slightly drier than OMC.

#### *(d) Drying*

The strength of a soil cement increases with age. A minimum curing period of 14 days is absolutely essential, although 28 days is better. During this period the material should be kept in a moist environment, sheltered from the sun and protected from the wind, in order to prevent excessively rapid surface drying, which may cause shrink cracking. The materials should be allowed to dry when compacted, and moistened by

spraying or covered with a plastic sheet, which allows temperatures to rise and gives an RH close to 100 per cent. The longer this moist-drying cure is allowed to go on, the greater will be the strength of the material.

### *C. Lime*

The theory of lime stabilization suggests five basic mechanisms.

(a) *Water absorption*: Quicklime undergoes a hydration reaction in the presence of water or in moist soil. This reaction is strongly exothermic with the release of about 300 kcal for every kg of quicklime.

(b) *Cation exchange*: When lime is added to a moistened soil the latter is flooded with calcium ions. Cation exchange then takes place, with calcium ions being replaced by exchangeable cations in the soil compounds, such as magnesium, sodium, potassium and hydrogen. The volume of this exchange depends on the quantity of exchangeable cations present in the overall cation exchange capacity of the soil.

(c) *Flocculation and accretion*: As a result of the cationic exchange and the increase in the quantity of electrolytes in the pore water, the soil grains flocculate and tend to accrete. The size of the accretions in the fine grain fraction increases. Both grain size distribution and structure are altered.

(d) *Carbonation*: The lime added to the soil reacts with carbon dioxide from the air to form weak carbonated cements. This reaction uses part of the lime available for pozzolanic reactions.

(e) *Pozzolanic reaction*: This is by far the most important reaction involved in lime stabilization. The strength of the material results largely from the dissolution of clay minerals in an alkaline environment produced by the lime and the recombination of the silica and alumina in the clays with the calcium to form complex aluminium and calcium silicates, thus cementing the grains together. The lime must be added to the soil in sufficient quantities in order to proceed and maintain a high pH, which is necessary for the dissolution of the clay minerals for long enough to allow an effective stabilization reaction.

#### *1. Effectiveness and proportions*

When 1 per cent of quicklime is added to the soil the exothermic hydration reaction dries the soil, removing between 0.5 and 1 per cent of water. The addition of 2 to 3 per cent of quicklime immediately provokes a reduction of the plasticity of the soil and the breaking up of lumps. This reaction is called the fixing point of the lime. For ordinary stabilization work between 6 and 12 per cent is used, similar to the amounts required for cement stabilization - the difference being that with lime there is an optimum quantity for each soil.

Sophisticated industrial procedures make use of high pressures and steam treatment in an autoclave with the proportion of lime rising to as much as 20 per cent. The products obtained are similar to those



obtained in the silica-lime industry. Lime stabilization is particularly well suited to pressure moulding procedures.

## 2. Types of lime

(a) *Non-hydraulic limes* are produced by burning very pure limestones. They represent the main source of lime for use in stabilization.

- *Quicklime* ( $\text{CaO}$ ): Quicklime is produced directly by burning the stone in kilns. The delicate conditions of storage and maintenance required can limit its use. Quicklime is extremely hygroscopic (i.e., it attracts water) and must be protected from moisture. It is a caustic material and must be handled with great care. It becomes very hot in the hydration stage (up to  $150^{\circ}\text{C}$ ). Weight-for-weight it is more effective than slaked lime, because it can supply greater quantities of calcium ions. In moist soils it can absorb the water required for its hydration.
- *Slaked lime* ( $\text{CaOH}_2$ ): Slaked lime is obtained by hydrating quicklime. Widely used for stabilization, it does not have the drawbacks of quicklime. Fat slaked limes do not have to be very finely crushed to be effective. Industrial qualities contain between 90 and 99 per cent of "active lime" while craft-produced lime may only contain between 70 and 75 per cent, with the rest being unburnt or excessively burnt materials. The proportions used for stabilization must be adapted in consequence.

(b) *Hydraulic lime* is similar to cement. Its use should not be considered unless other qualities of lime are not available. Natural hydraulic limes are more effective stabilizers than artificial hydraulic limes.

(c) *Agricultural limes* are used to improve agricultural soils and usually have no stabilizing effect at all.

## Additives

Some additives mixed with limes in small quantities can have special effects.

(a) To increase the reactivity of the soil:

- Caustic soda;
- Sodium sulphate;
- Metasilicate of sodium;
- Carbonate sodium;
- Sodium aluminate.

The quantity used varies from 0.25 to 2 molecular grams per litre of the water used for compaction.

(b) To increase compressive strength:

- Portland cement is added in quantities of up to 100 per cent of the lime.

(c) To increase the effectiveness of stabilization for sandy silt soils and reduce the swell due to the slaked lime:

- Magnesium sulphate is added at a rate of about one quarter of the weight of the lime.
- (d) To make the soil waterproof:
  - Potassium sulphate;
  - Bitumen products;
  - Other water repellents.

### 3. *Production procedure*

#### (a) *Crushing*

This operation is important and must be carried out with the greatest care. The more finely the clay is crushed, the more active the lime will be in attacking the clay. The operation may be difficult because clay is highly cohesive. Very moist soil can be dried and broken up with quicklime. Stabilization will be effective if at least 50 per cent of the aggregated clay is crushed to a diameter of less than 5 mm.

#### (b) *Mixing*

The mixing must be very carefully carried out in order to ensure the intimate mingling of the soil and the lime. For very plastic soil, the process should be carried out in two stages, with about one to two days between them. This gives the lime a chance to loosen the lumps. This two-stage procedure may nevertheless reduce the effect of the lime on strength. The homogeneity of the mix can be checked by observing the uniformity of its colour. No trail of lime not incorporated in the soil should be visible.

#### (c) *Hold-back time*

If the moist method is used, it is advantageous to allow the mixture to rest after mixing. A period of at least 2 hours should be allowed for quantities of lime above the fixing point; a period of 8 to 16 hours is preferable. The effect on dry density is negligible, but greater strengths can be achieved.

If the plastic approach is used, everything is to be gained by allowing the mixture of soil and quicklime or slaked lime to rest for several weeks. This is particularly the case for renderings which become greasier and more adhesive.

#### (d) *Compression*

Dry density is very sensitive to the degree of compaction, especially for high proportions of lime. The moisture content will be close to the optimum, on the moist side, when an adequate hold-back time has been allowed (longer for higher quantities). The exothermic reaction set off by the quicklime consumes close to 1 per cent of the moisture content per percentage of quicklime added. The moisture content will thus be corrected as OMC is approached during the second mixing stage.



### (e) *Drycuring*

An increase in compressive strength can be obtained if the curing period is extended. This phenomenon lasts several weeks and persists for months. It is even better in a warm, humid environment. Lime-stabilized products can be very advantageously exposed to high temperatures (+/- 60). Curing in the sun under a sheet of plastic or in a tunnel built of corrugated iron makes it possible to achieve such high temperatures and relative humidities. Research carried out at the University of Denmark has shown that very good products can be obtained by drying for 24 hours in an autoclave at 60-97° C with an RH of 100 per cent.

### *D. Bitumen*

If it is to be used, the bitumen must be either heated; or mixed with solvent resulting in "cutback"; or dispersed in water as an emulsion. It is the two latter techniques which are used for stabilization.

Cutback and bituminous emulsions come in the form of microscopic droplets in suspension in a solvent or in water. The stabilizer is mixed in the soil, and when the water or solvent evaporates the droplets of bitumen spread out to form very thin strong films which adhere to and cover the soil. Bitumen improves the water-resisting properties of the soil (less absorption by clays) and can improve the cohesion of soils with non-cohesive soils, by acting as binder.

#### *1. Effectiveness and proportions*

In order to obtain uniform distribution of the bitumen throughout the soil, it is better to use a technique making use of large quantities of water. The adobe technique is thus the most suitable. Normally 2 to 3 per cent of bitumen is added, but this can rise to 8 per cent. Proportions vary in accordance with the grain size distribution of the soil because bitumen stabilization involves the coating of the specific surface of the grains. The values given here are for the bitumen prior to being diluted in a watery suspension or by a solvent. The bitumen has only a very slight effect on the colour of the material and has no typical odour once the stabilized products have dried.

- *Soil:* Bitumen stabilization is most effective with sandy or silty soils. It is not suitable for fine soils in dry regions, where the pH and salt content of the soil may be high.
- *Organic matter and sulphates:* Their presence in the soil hinders the efficiency of bitumen stabilization, as their adhesion to the grains prevents the adhesion of bitumen. Acid organic matter (e.g., forest soils) are very harmful. The neutral and basic organic matters found in arid and semi-arid regions are not particularly harmful.
- *Salts:* Mineral salts are very harmful. They can be neutralized by adding 1 per cent of cement. When bitumen stabilization is

carried out on an industrial scale, salt contents of more than 0.2 per cent are not accepted, but sometimes up to 6 per cent of sodium chloride can be accepted.

## *2. Types of bitumen*

When bitumen is used for stabilization it is generally in the form of cutback or emulsion. Both forms break down on drying, and this breakdown can be slow or fast. Rapid breakdown is suitable for temperate climates and slow breakdown is better for hot climates.

### *(a) Cutbacks*

These are bitumens to which a volatile solvent has been added, making them less viscous. Solvents can be gas-oil, kerosene, and naphtha. Some of them dry slowly, some moderately quickly, while others dry rapidly. They cannot be used in the rain and are flammable. Their viscosity is indicated by an index number: 0 = very fluid, 3 = viscous. RC 250 is a cutback which is widely used in the United States.

### *(b) Emulsions*

Bitumen (55 to 65 per cent) is dispersed in water with the help of an emulsifying agent (1 to 2 per cent). This agent also keeps the bitumen in suspension.

There are two sorts of emulsion.

- *Anionic*: unusual and not suitable for all aggregates; used mostly in Europe.
- *Cationic*: more widespread and compatible with virtually all soils, used in particular in the United States.

Emulsions are usually very fluid and mix easily with soil which is already moist. They are less stable than cutbacks, and there is a danger of the water and bitumen bond breaking down (separation).

## *3. Production procedure*

### *(a) Mixing*

The effectiveness of bitumen stabilization depends very largely on this operation. Too much mixing can increase water absorption after drying because of the premature breakdown of the emulsion. If the mixing is carried out in the liquid or plastic state (adobe, cob, mortar, or rendering), no problems of this sort are encountered.

However, if the soil is going to be compacted, the mixing should be carried out at OMC. When soils are already moist, care must be taken not to add excessive quantities of stabilizer (water and bitumen). Wet strength and impermeability may be reduced.

When low proportions of bitumen are used (e.g., 2 per cent), it is preferable to add the bitumen to a small quantity of soil, and then to



mix this small quantity with the remainder of the soil. This applies particularly to cutback. Emulsions should be diluted in the mixing water.

(b) *Hold-back time*

When bituminous stabilizers with slow or moderately quick breakdown time are used, it is possible to wait between mixing and moulding. When products with rapid breakdown times are used, operations should follow one another without delay.

(c) *Compaction*

20 to 40 daN/cm<sup>2</sup> is enough and leaves the material a fairly porous structure in order to facilitate the evaporation of volatile solvents while ensuring good dry density. When turning out from the moulds the bitumen acts as a release product. The blocks have an attractive appearance with sharp arrises.

(d) *Curing*

Cutback and emulsion which break down rapidly shorten drying times. It is preferable to allow bitumen-stabilized material to cure in dry air rather than in a moist environment. Compressive strengths are related to the quantity of bitumen used and the duration of the drying period. These two parameters should be determined in advance by means of tests to find out what the optimum values are. The loss of volatiles is greater for longer curing periods and higher temperatures, and this has a beneficial effect on absorption and expansion. Above 40°C, however, no further improvement is noted.

### *E. Resins*

A great deal of recent research work has been concentrated on chemical stabilization by means of chemical resins, particularly in the field of civil engineering. The object of this research has been to achieve an increase in local-bearing capacity while at the same time reducing the weight of stabilized-earth courses. The highest shear strength combined with the greater elasticity of the wearing courses has been sought. These objectives, which correspond to civil engineering requirements, are not necessarily applicable to the construction of buildings, except for such horizontal surfaces as footways or stabilized slabs. Quite extraordinary results have been obtained with resin stabilization. The considerable extra cost compared with ordinary stabilization procedures, however, remains the greatest barrier to its widespread use.

The vigorous action, rapid setting, and easy incorporation into the soil as viscosity are comparable to water. Very moist soils can be solidified.

Their high cost and sophisticated production technology only make them available in industrialized countries. The quantities required are

large compared with conventional stabilizers. The products are toxic, difficult to handle, requiring the use of catalysts, sensitive to water, and their service life is uncertain as the products are biodegradable.

These resins are made up of long-chain molecules resulting from the linking (polymerization) or certain chemical agents (monomers and polymers). They can be used in two different ways:

(a) Monomers are added to the soil at the same time as the catalyst: reaction between the soil and the monomers is immediate as is polymerization. This is the case of abietic resins, for example.

(b) A polymer is formed in advance by synthetic or natural means and then added to the soil as a solid, solution, or emulsion.

The resins act in different ways, as flocculants, as dispersants or as acids. The majority act to render the soil impermeable, while the more sophisticated can improve the cohesion of the soil.

The following are some popular types of resins:

(a) *Gum Arabic* is obtained from the acacia tree. Its impermeability is low because it is soluble in water. It acts primarily as a flocculant, helps to increase dry compression strength, and slows capillary absorption of water by acting on the kinetics of this phenomenon.

(b) *Palmo-copal*: Copal is a resin obtained from certain tropical trees. Palmo-copal is a solution of copal obtained by pyrogenation from palm oil. The amount required varies from 3 to 8 per cent for sandy soils. Another variety, manila copal, is the only copal resin which has an impermeable capacity.

(c) *Wallaba resin* is a water repellent.

(d) *Colophane* is obtained during the distillation of turpentine essences from oily pine resins. It is soluble in organic solvents and in aqueous alkaline solutions. Colophane resin forms a gel after reacting with certain metallic salts (iron and aluminium). It reduces the water absorption capacity of soils.

(e) *Vinsol* is also obtained in the production of turpentine. It is used in acid soils at critical control rates (+/- 1 per cent). Water repellent improves cohesion but does not affect compressive strength.

(f) *Lignin* is a by-product of the paper industry. It is a sort of alkaline resinous liquor with an impermeable capacity. It is soluble but can become insoluble when reacted with chrome. Chromo-lignin is, unfortunately, an expensive product.

(g) *Molasses*: Sugar aldehydes from dehydrated molasses can be polymerized at high temperatures with phenolic catalysts. The resinous material obtained has characteristics similar to those of a naturally occurring asphalt and synthetic resins.

(h) *Ethylcellulose*: This is a synthetic resin which has been tested but without satisfactory results.

(i) *Carboxymethyl cellulose*: This is a non-ionic stabilizer with a coagulating action and is water-soluble.



(j) *Shellac* confers excellent strength to sandy soils but the stabilized material does not stand up well to water.

## *F. Natural products*

### *1. Mineral products*

These products are used to correct the grain size distribution of soils. For example, sands can be added to clays and *vice versa*. Sometimes very specific soils are selected in order to obtain very particular effects. A good example is bentonite, which is added in small quantities to the soil being treated. This smectic clay has powerful degreasing properties and expands in the presence of water, thus preventing the passage of water.

Some soils (volcanic sands in particular) have natural pozzolanic properties. They can be used for stabilizing clayey soils but often require the addition of at least 30 per cent of lime or cement before becoming an effective binder which in turn will stabilize clay when added at a rate of about 8 per cent.

### *2. Animal products*

These are only very rarely used for stabilizing walls or solid elements of a building. They tend to be reserved for the stabilization of renderings.

(a) *Excrement*: All sorts of excrement are used. Cowpats are undoubtedly the most widely employed, although they are better used as a manure or fuel. This particular excrement has in the final analysis only a very limited effect on water resistance and reduces compression strength. Other traditions make use of horse or camel dung, or of pigeon droppings. The action of these sorts of excrement is probably due to the presence of fibre (mixed straw), phosphoric acid and potassium. The use of animal urine is also known. Horse urine when used to replace the mixing water (e.g., for daub) effectively eliminates cracking and gives a marked improvement in the ability of the soil to stand up to erosion. Surprisingly good results can be obtained when it is combined with lime.

(b) *Blood*: The use of bull's blood is known from Roman times. When combined with lime or polyphenols, stabilization with bull's blood is effective. The blood must be fresh and not be in powder form.

(c) *Fur and hair*: Animal hair and fur play much the same role as some vegetable fibres. Their use is generally reserved for stabilizing renderings.

(d) *Casein*: Proteinic casein (middle fraction of the protides of milk) is sometimes used in stabilization in the form of whey combined with bull's blood. Certain milk powders have been tried and gave good results. "Poulh's soap" is also used. This is diluted casein. It is beaten

like a paste, after first being mixed with brick dust prior to being added to the soil.

(e) *Lime*: Lime can be prepared from shells or coral. This is still done in some countries such as Senegal and Somalia.

(f) *Glues*: These can be used for stabilization, particularly for renderings. Animal glues are produced from horn, bone, hooves, and hides.

(g) *Termite hills*: Termites secrete an active substance, which appears to be a non-ionic cellulose polymer of the polysaccharide type. Termite hills stand up well to rain and their soil can be mixed with another for the production of blocks. The substance has been synthesized by research workers in South Africa, but costs three times as much as cement.

(h) *Oils and fats*: Fish oils and animal fats can serve as waterproofing agents. Similarly the stearates contained in animal fats play the same role.

### 3. Vegetable products

(a) *Ashes*: Hardwood ash is rich in calcium carbonate and has stabilizing properties but is not always suitable for soils which may be suited to lime stabilization. Classic proportions suggest the addition of 5 to 10 per cent ash. Ashes improve the dry compression strength but do not reduce sensitivity to water.

(b) *Vegetable oils and fats*: If they are to be effective, vegetable oils must dry quickly so that they harden upon contact with the air and are insoluble in water. The use of castor oil is highly effective, but it is extremely expensive. Coconut, cotton and linseed oils are also used. Kapok oil prepared first by roasting kapok seeds, turning them into a flour which can then be transformed into a paste (20 to 25 l of water to 10 kg of powder) can be effective. This depends on the quality of the seeds and the roasting process, which increases the yield, as well as the length of time it takes to prepare the paste (6 hours boiling). Palmitic acid is obtained from saponified palm oil precipitated by 25 per cent HCl. About 1 kg of palmitic acid is obtained per kg of palm soap in solution.

## PART TWO

# DESIGN AND CONSTRUCTION TECHNIQUES

### I. BASIC CONSIDERATIONS

Problems associated with chronic humidity and dampness can be avoided by adopting a good approach to the design and execution of the earth structure.

In order for water to cause problems, the following three conditions must coexist:

- (a) Water must be present on the surface of the building;
- (b) There must be an opening in this surface, such as a crack or window, which allows the water to enter;
- (c) There must be a force - pressure, gravity of capillary action - facilitating the entry of water into the opening.

The most fragile points in earth structures and those most vulnerable to water action and moisture are the bottom and the top of the walls. There are other localized weak points as well, such as the reveals of openings, parapets of terraces, gargoyles, and bonds between different materials, such as between earth and wood. These are the points which require special care and regular maintenance.

Capillary rise at the base of walls, beginning in the foundations, has several origins, including seasonal changes in the groundwater table, retention of water by the roots of shrubs, defective sewers, a lack of drains for the building, and standing water at the foot of walls. Persistent dampness can bring about a weakening of the base of the walls. The material passes from the solid to the plastic state and the walls can no longer bear loads, increasing the likelihood of collapse. Dampness favours efflorescence by salts attacking the material and causing formation of hollows. Insects and rodents attracted by the damp conditions can cause further deterioration to the wall.

Above ground level, the base of the walls may be eaten away for any of the following reasons: water splash from gargoyles, water thrown up by passing vehicles, washing of floors indoors, surface condensation (morning dew), run-off at the foot of the wall (gutters too close to the wall), surface rendered impermeable (watertight walkway or rendering) preventing evaporation or encouraging condensation between the earth wall and the waterproof rendering, the growth of parasitical flora (moss) and efflorescence.

Damage can also occur in the following ways:

- (a) Water infiltrates through structural cracks (settlement, and shearing) and shrink cracks caused by repeated dry-wet cycles, unfilled holes left by formwork clamps, and by defective mortar joints causing capillary action, and hollowing of walls.



(b) Water runs off at the junction of reveals and earth walls (support, lintel) and infiltrates between the masonry of the reveal or the wooden frame and the soil causing localized deterioration.

(c) Rain and variations in temperature can bring about the decomposition of the material. Clays are washed out, reducing the cohesion of the soil.

(d) When an earth wall is protected with a rendering which prevents the movement of water vapour, condensation on the cold surface of the wall (indoor walls in summer; outside wall in winter) or condensation between the wall and the rendering may cause the wall to deteriorate.

(e) Water may penetrate at the point where floor or roof beams pass through earth walls.

(f) Water runs and gets in where poorly designed gargoyles pass through walls and are unprotected at their entry and exit. Accumulation of earth can stop up gargoyles, resulting in standing water, absorption and capillary action.

(g) Parapets unprotected by a projecting cap or which are cracked or covered with a defective rendering encourage water run-off and infiltration. Objects placed against parapets such as plants requiring watering and poorly drained terraces can cause water and dampness to be retained.

(h) Cracked terraces and damaged surfacing facilitate infiltration.

Like all structures, those built with earth may be subject to the effects of structural defects which occasionally cause irreversible damage. The use of soil as a construction material demands scrupulous respect of codes of good practice for the material and building systems. Structural defects may, however, be the result of causes which have nothing to do with the earth itself. These may include problems related to the site, e.g., settlement and earthslips, and natural disasters, which can have very serious effects on structures, particularly when they are poorly designed, badly built and carelessly maintained.

The principal causes of structural defects can be summarized as follows:

(a) Stresses on the material to which it is unsuited, such as tensile and bending stresses. Earth only functions well in compression. Other types of stress require other materials: wood, reinforced concrete and steel (used as ties, lintels etc.);

(b) Chronic dampness decreases the strength of the material, even in compression;

(c) Construction on poor ground which cannot bear the loads transmitted to it, or on moving ground (slip, uneven settlement, heave and swell);

(d) Poor design of the building: under-designed or off-centre foundations, inadequately braced walls, untied walls, walls which are too high, walls with too many openings, or made of composite materials; excessive loads in the form of floors, roofs, occupancy and concentrated



loads; construction systems unsuited to the use of earth as a building material;

(e) Poor construction: poor quality material (e.g., unsuitable soil, poor bricks); poorly implemented construction techniques (e.g., mistakes in the bond, vertical cracking along joints); incorrectly mixed mortar; poorly designed openings, no ties, no protection at the top and bottom of walls;

(f) Related causes: climatic influences (e.g., wind action on damp wall, loss of material); action of living organisms: plant parasites (mosses, lichens), rodents, insects (termites).

## II. THE SUBSTRUCTURE

### *A. Foundations - basic rules*

Unburnt soil structure with solid walls made up of smaller units such as bricks, adobe or compressed blocks, or monolithic walls made of cob or rammed earth can be approached along the same lines as conventional masonry.

Conventional foundation systems and materials are perfectly satisfactory. Foundations should be deep enough to be:

- (a) Constructed on good soil. Be particularly wary of expanding soils or soils liable to severe subsidence (e.g., black cotton soils);
- (b) Protected against the action of surface water and damp;
- (c) Protected against frost;
- (d) Protected from wind erosion which can wear away foundations (in severe storms);
- (e) Protected against the effects of works in the vicinity (roads, gardening, agriculture);
- (f) Protected from rodents and insects (e.g., termites).

Foundation blocks must be solid and be capable of providing effective transfer of loads to the soil without themselves being affected. To do this they must be made of strong materials.

Stabilized soil is not recommended and should only be used in exceptional circumstances on dry and well-drained sites. If it is the only possible solution, the foundations are built in stabilized rammed earth in an open trench, or in compressed blocks.

Stabilized earth foundations may be set on blinding concrete or on stoned pitching or a layer of sand. A coarse concrete or reinforced concrete slab in the bottom of the trench represents a considerable improvement.

In wet regions, soil foundations, even if stabilized, are out of the question. If there is no other alternative, steps must be taken to protect the surface or make it waterproof (coating with hard materials, waterproof membrane etc.).

All other conventionally adopted materials are suitable. Foundation slabs can be built in stone. In this case rubble can be used, laid as blockwork, over which a mortar is poured. They can also be coated with mortar and tightly packed against one another. Care must be taken to lay the rubble in a good bond to avoid cracking along the joints. This can be done by staggering the vertical joints.

The foundations can also be built in coarse concrete. The rubble is, in this case, embedded in the successive layers of concrete enveloping each layer of stones, covering these to a depth of at least 3 cm. The stones should not touch one another.

Burnt bricks are also suitable for making good-quality foundation slabs. Good-quality non-porous burnt bricks should be used, and care should be taken to construct the bond properly.

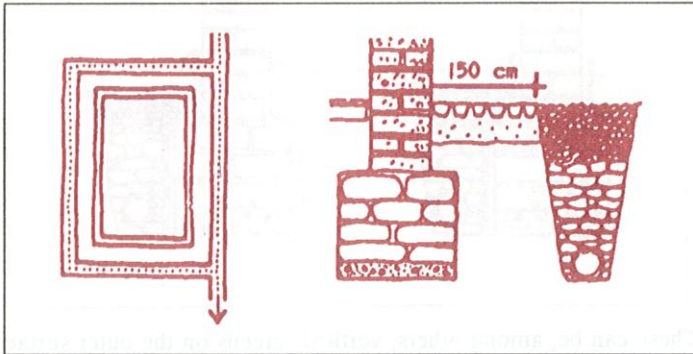
Finally, foundation slabs can be built using reinforced concrete and modern techniques.

## *B. Foundations - design details*

### *1. Foundations for normal soil conditions*

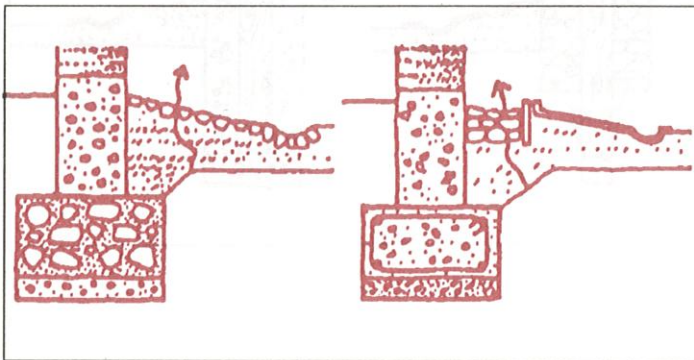
For normal soil conditions the design of foundations should take the following into consideration.

#### *(a) Drainage*



Good peripheral drainage is essential if water is to be kept away from the building. It must be constructed with the greatest of care to ensure its effectiveness. Drains should be built during excavations at the bottom of the trenches, close to the foundations or at a short distance (1.5 m) from the foundations. A channel (in burnt clay or some other suitable material) is laid at the bottom of the trench, which collects water and removes it by means of a regular gradient. The drain is then filled with stones and gravel to create a filter system.

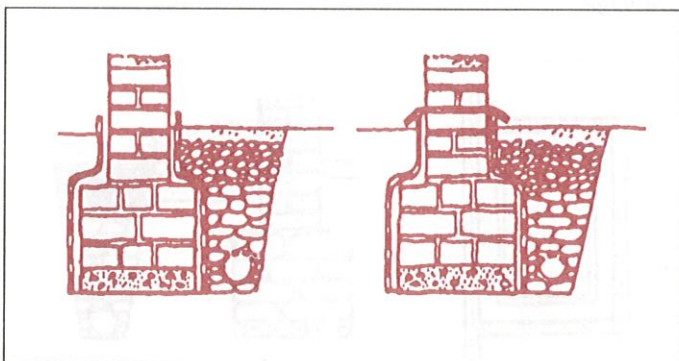
#### *(b) Gradient and gutters*





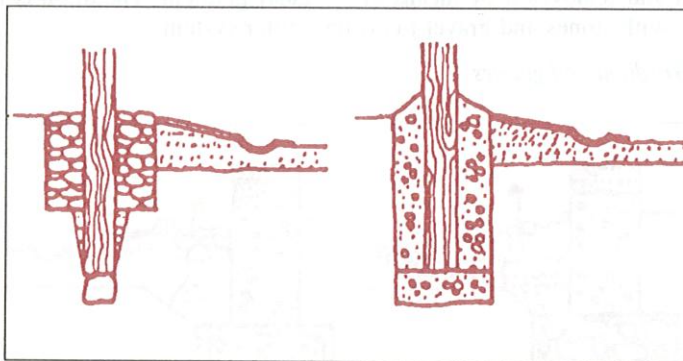
The soil outside the building is specially arranged. A gradient of 2 cm per m or more allows surface water to run off into a properly designed gutter some distance from the wall. Waterproofing the soil should be avoided (impervious pavement etc.) so as not to hinder the evaporation of moisture in the soil. It is better to spread gravel over a narrow strip. Trenches should be backfilled in compacted layers sloping towards the outside.

(c) *Moisture barriers*



These can be, among others, vertical screens on the outer surface of foundations or horizontal screens serving as an anti-capillary course between the foundations and the base course. Such moisture barriers must be perfectly continuous and may not be cracked or defective. A damp course can be made either of water-repellent concrete ( $500 \text{ kg/m}^3$ ) or a bituminous product.

(d) *Wattle*



Where daub or clay-straw is used, it is wise to take steps to treat the wood, particularly posts fixed in soil. Wooden posts should be embedded in the stone or concrete foundation slab. Care must be taken to drain around the structure.

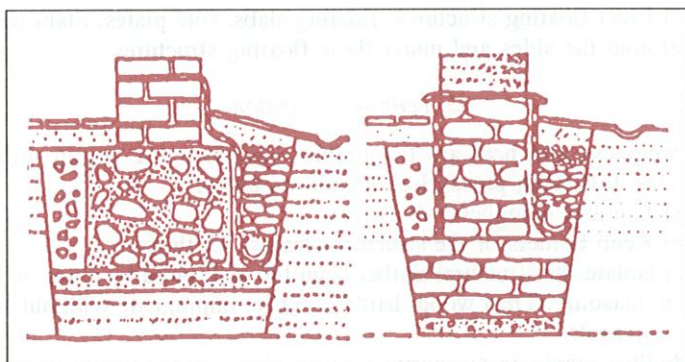
## *2. Foundations on unstable soils*

Soils in arid regions are often very unstable. Alluvial and dark tropical soils in particular are very expansive. The instability of these soils is mainly due to water action reducing their cohesion. Special treatment of the soil in the foundation or special foundations may be required.

For expansive soils:

(a) Keep water at a distance. Peripheral drainage is essential as well as a gradient sloping outwards (at 5 cm per m) at the foot of the wall.

(b) Dig trenches down to good soil, compact the bottom of trenches and backfills under slabs and close to the building.



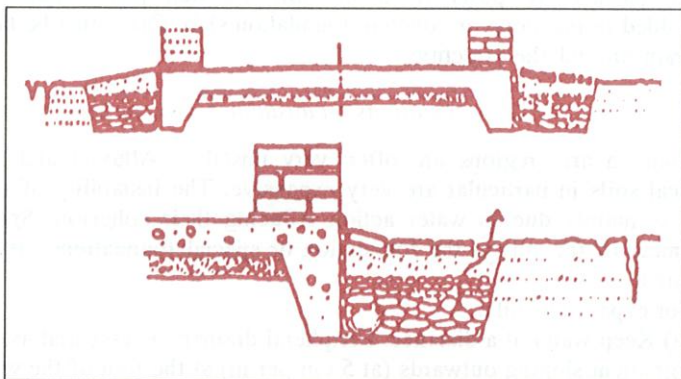
(c) Build rigid foundations: stones, reinforced concrete, piles, on fills of coarse gravel and stones.

(d) Stabilize the soil so that it will be less sensitive to water.

(e) Erect sufficiently flexible structures: wooden or metal frames.

(f) Construct extremely heavy walls so as to counteract heave.

For soils lacking in cohesion:



(a) Provide for the escape of water and drain the edges. Do not hinder water evaporation.

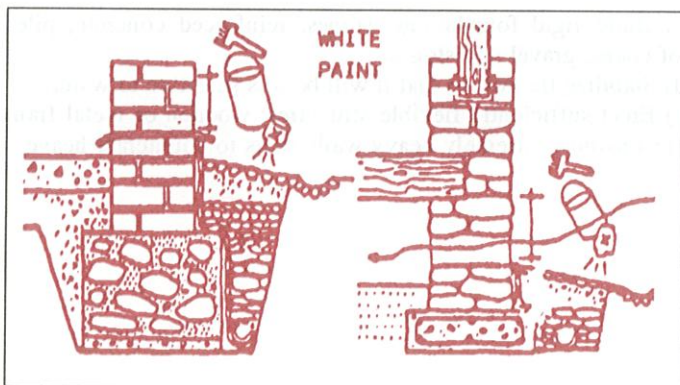
(b) Ram the soil and/or stabilize. One method is to first flood the soil so that it is already packed once it has dried.

(c) Erect floating structures: floating slabs, sole plates. Stabilize the soil around the sides and under these floating structures.

### *3. Termite protection*

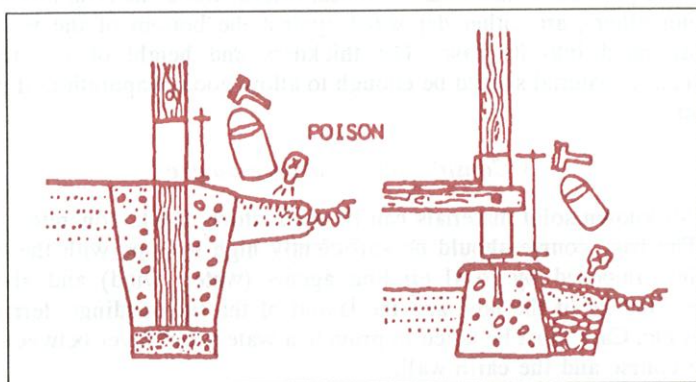
Dampness and heat are favourable conditions for termite infestation. The following precautions should be taken:

- (a) Combat dampness: drainage;
- (b) Keep borders of the structure clean at all times;
- (c) Isolate the structural timber from the soil: build on studs or piles built in masonry. Treat wood: harden by fire, impregnate with old sump oil, or creasote;
- (d) Plug cracks in masonry;





- (e) Paint the base courses white in order to make boreholes visible;



- (f) Create a chemical barrier by treating the soil with antitermite insecticides;

- (g) Stabilize foundations or base courses by incorporating crushed glass into the soil.

### *C. Base courses - basic principles*

In regions with a rainy climate or exposure to natural water disasters (tropical cyclones, flooding etc.), the base course is an indispensable element that ensures that water is kept out of the structure as a whole. The basic principles of protection involve the following.

#### *1. Wearing layer*

This basic technique is particularly suitable for soil base courses exposed to water erosion - e.g., splashing, condensation etc. A solid layer of soil is applied to the base of the wall, and will be affected before the base course. Regular maintenance of this protective layer is essential. Wearing layers of this sort should preferably be accompanied by a system for draining run-off water away from the base of the wall collected: e.g., a ditch or a gutter.

This procedure is just as good for buildings with overhanging roofs as for those with flat roofs topped by parapet walls.

Traditional architecture has made extensive use of this principle of protection, e.g., earth architecture in Mali, Morocco, Saudi Arabia and elsewhere. This protection technique offers the advantages that it is economical and easy to use.

## *2. Material deposited at the base*

Such protective materials as stones, bricks, wood, matting and tiles, among others, are either deposited against the bottom of the wall or incorporated into its base. The thickness and height of the added protective material should be enough to allow good evaporation of pore water.

## *3. Construction of a base course*

All known solid materials can be used: stone, brick, concrete.

The base course should be sufficiently high to cope with the constraints imposed by local eroding agents (water, wind) and should follow the lie of the land and the layout of the surroundings: terraces, steps etc. Care must be taken to provide a waterproof layer between the base course and the earth wall.

The height depends on local rainfall patterns, the likelihood of flooding, the overhang of the roof, and the evaporation of the water accumulated in the base of the wall.

- Dry regions: 0.25 m
- Average rainfall: 0.40 m
- Heavy rainfall, small roof overhang: 0.60 m or greater.
- Area susceptible to flooding (e.g., at the side of a watercourse): 0.80 - 1.00m, to allow a good evaporation of pore water absorbed by the base.

## *D. Base courses - design details*

### *1. Stabilized brick*

This material can only be used very infrequently, when it is certain that the site of the structure is dry, well-drained and protected against infiltrating water.

The entire base course can be built in stabilized brick, observing the rules of sound construction (bond in particular) or only the facing. In the latter case the difference in strength between the stabilized and non-stabilized brick must not be too great.

It is recommended that this type of base course is finished with a rendering which allows the passage of water vapour. The rendering must end above the level of the ground if capillary absorption is to be avoided.

The edges of the structure must be laid out with care: slope away from the building, peripheral drainage belt, drainage ditch for surface water.

### *2. Burnt brick*

Burnt bricks used for base courses should not be porous. If they are, the same precautions as for stabilized brick should be adopted. In

addition, burnt brick can also be used as a facing only or to make a protective coating of bricks and stones. This type of facing is an attractive solution for the repair of the lower part of a building being restored.

### *3. Stone*

Depending on its permeability, stone is regarded as a more or less waterproof material. Good-quality stones can be left visible, but care must be taken to rake out the joints so as to prevent water from infiltrating. Raking-out facilitates the bonding of any rendering.

### *4. Concrete or concrete elements*

Concrete, when correctly mixed ( $250 \text{ kg/m}^3$ ) can be considered to be waterproof but it is advisable to protect it with a damp-proof membrane, particularly where it is buried or where the concrete is on the lean side.

Concrete blocks, whether solid or hollow, can be used for base courses but they are best for light earth walls made of straw- earth, for example. A damp-proof membrane screen is essential.

### *5. Stabilized rammed earth*

Rammed earth can be stabilized throughout the entire thickness of the base course or on the surface alone. The second procedure has the advantage of being more economical but requires very careful execution. The non-stabilized and stabilized rammed earth are rammed simultaneously, layer after layer, the stabilized earth being rammed against the form on the outer facing of the wall.

A surface coating can also be applied down a vein of lime mortar in each compacted layer. The mortar is thrown with a trowel and its thickness controlled by a mark on the formwork to ensure good finishing of the wall.

### *6. Cladding*

Cladding (slabs of wood or shingles, nailed on to laths) can be fitted against the base course. This type of work often requires a wooden lattice to carry the cladding. An air space increases the effectiveness of the system by permitting ventilation and evaporation of moisture which might be retained behind the cladding.

Woven reeds and straw matting make cheap cladding but must be regularly maintained and periodically replaced. Cladding has the added advantage of offering thermal protection, particularly when ventilated.

### *7. Surround, footway*

This can be a simple timber positioned lengthwise in front of the base course, immediately below the roof gutter to catch any drips. Bottles, tin cans or stones driven into the earth are just as satisfactory.



Upended posts, held by cross pieces and retaining an earth pavement form a more elaborate system. The pavement should have a slight gradient and be provided with a drainage ditch.

### ***8. Encrusted renderings***

A rendering covering the base course and encrusted with gravel or stone chippings, constitutes a good wearing layer.

### ***9. Temporary protection***

During the rainy season simple tiles or flat stones positioned against the base of the wall form satisfactory and extremely cheap protection.

### III. WALLS

#### A. Walls - basic principles

Experience has established an empirical relationship for earth brick walls, where the thickness of walls should be at least one tenth of their height. The minimum thickness of rammed earth walls in single-storey structures should be taken as 30 cm, while with a floor it should be 45 cm. Similarly the distance between partition walls or buttresses or expansion joints (dry joints planned in advance or kept strictly away from openings) should not exceed 5 to 6 m.

Earth walls made of adobes or compressed blocks must satisfy the same requirements with regard to bond as brick or stone walls. Walls must be protected with particular attention to the prevention of capillary rise at the base, condensation of vapour on cold walls, and humid rooms, as well as rain, frost and snow. Earth walls or parts of walls exposed to erosion due to wear - bottoms of walls, corners, tops of walls, parapets, reveals in openings, etc. - must be protected by a rendering or "hard" masonry work. Surface hardening occurs with a risk of smouldering where wood is incorporated in the structure (ties, for example).

The mortar used for joints should have the same compression strength and erosion-resistance as the bricks. If the strength of the mortar is less, erosion and infiltration of water will occur and bricks will deteriorate. If the strength of the mortar is greater than that of the bricks, the bricks will erode, water will stand on the exposed surface of the mortar, and aggravate the erosion of the bricks.

The mortar should be checked in prior tests for shrink, adhesion, erosion and compressive strength.

Stabilized mortar must be used for stabilized bricks. If the texture and water content of the mortar is different from those of the brick: the proportion of cement or lime in the mortar must be increased from 1.5 to 2 times in order to achieve the same resistance as the stabilized brick.

The shrinkage of the joints causes a horizontal crack in the wall of from 1 to 2 mm per 5 m. The settling of the joints under the load causes a vertical shrink of the wall from 1 to 2 cm per 3 m.

In principle, good construction practice should give consideration to:

(a) *Texture of the mortar*: sandier than that of brick with a maximum grain size of 5 mm, but preferably from 2 to 3 mm;

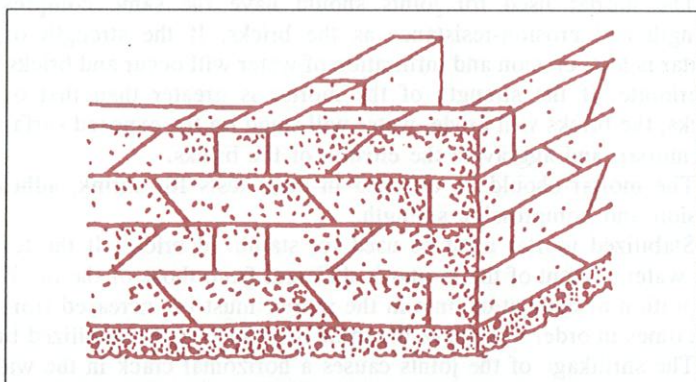
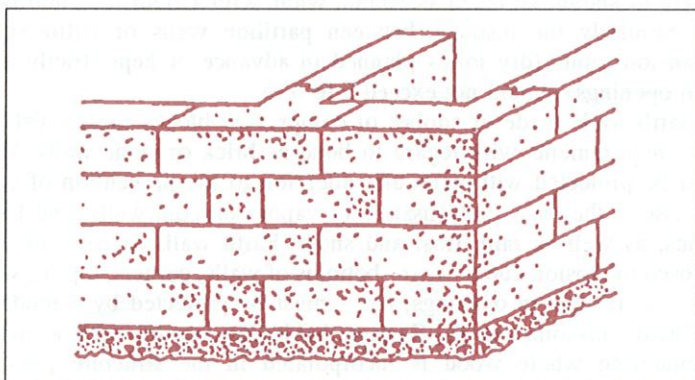
(b) *Thickness of joints*: horizontal and cross joints should have a maximum thickness of 1 to 1.5 cm, with a maximum tolerance of 2 cm for adobes;

(c) *Execution*: stabilized bricks must be presoaked and the bed thoroughly wetted. Mortar must be spread over the joint faces of the brick and the right quantity must be used. The brick is laid down rather than tapped. Protection against the sun and wind is recommended;

(d) *Jointing*: immediately after laying, rake out to a depth of 2 to 3 cm, joint up flush with mortar, and firm with a jointing tool.

## *B. Brickwork*

### *1. General rules*



The bond of adobe and compressed block walls must be carefully worked out (position of the joints). A poor bond can cause structural faults: e.g., vertical cracking. The rules which apply to plain brickwork are the same as those for burnt brick. Rammed earth moulded in adjustable forms should be treated as masonry with a large bond, where the cross joint must be staggered at least one quarter of the length of the form and provided with perfect toothing at corners and wall joints. The dimensions of the forms must accordingly be adapted to the bond planned in the design of the project in relation to the extreme dimensions of the design. The joints can be straight (Morocco, Peru, for example) or inclined at an angle (France, for example) and, if possible, grooved for better bonding.

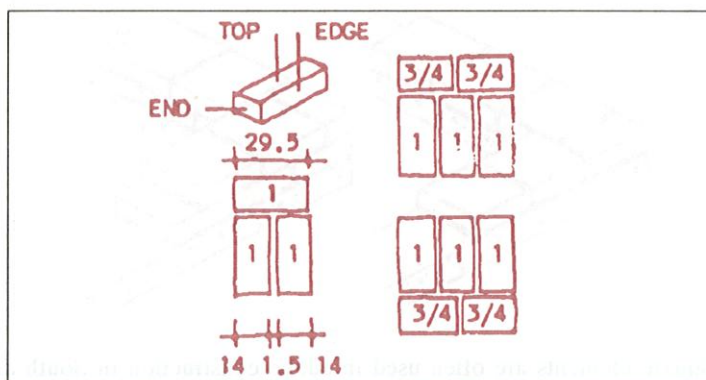


Bricks or earth blocks have six surfaces: a top and a bottom, two ends and two edges. The bonds in which the bricks are laid are named after the places where they are widespread and the pattern they make on the surface of the brickwork.

*Headed bond:* the brick is set in such a way that its greatest dimension is contained in the thickness of the wall, one of its ends appears on the surface.

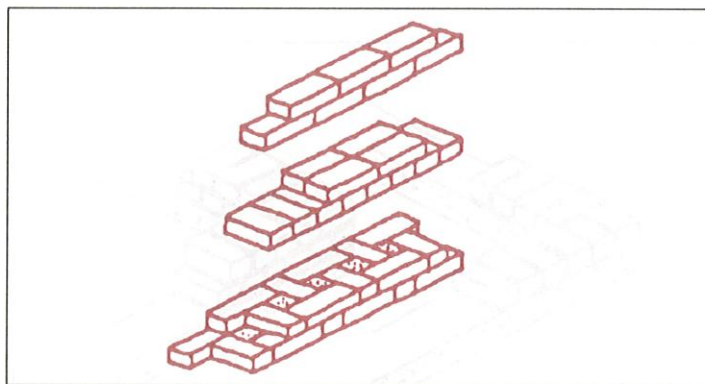
*Stretcher bond:* the greatest dimension and one edge are visible.

*Tile bond:* the greatest dimension and one face are visible - to be avoided since the brick is set in the cleavage plane.



*Heading bond:* the two ends of the brick are visible on both surfaces of the wall.

*Modulated bond:* brick walls are usually laid using complete bricks, but three-quarter bats, and half-bats are also used. The bonds in pillars often use three-quarter bats.

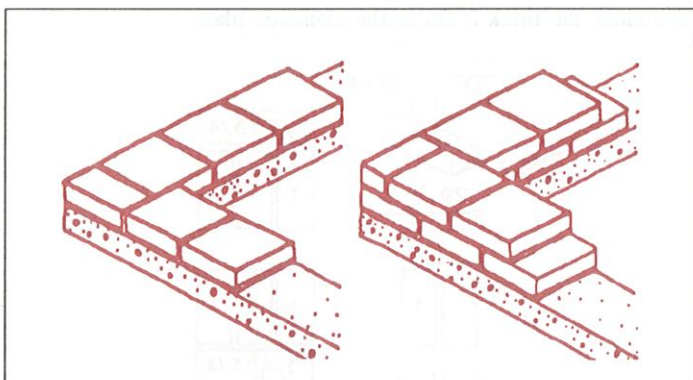


The distance between two cross joints on the surface of the wall, from one course to another, should be not less than one quarter of a stretcher. Superimposed joints result in vertical cracking. Such poor

work must be avoided. The following rule applies to overlapping of joints: In the thickness of the wall, bonded rising joints running in one direction should overlap by no more than three quarters of the length of a brick. The sum of the length of overlap of vertically bonded through joints should not exceed the length of a brick.

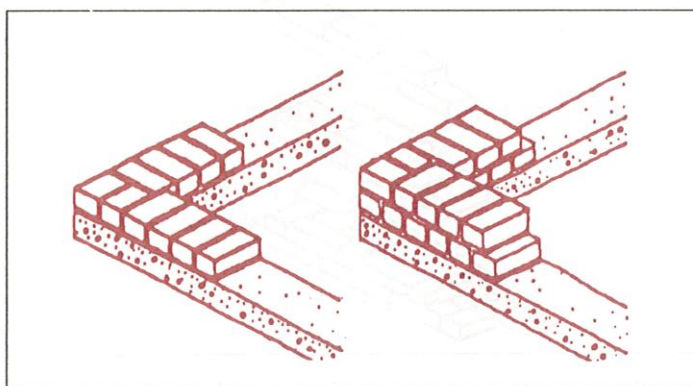
## 2. Conventional bonds

### (a) Square bricks

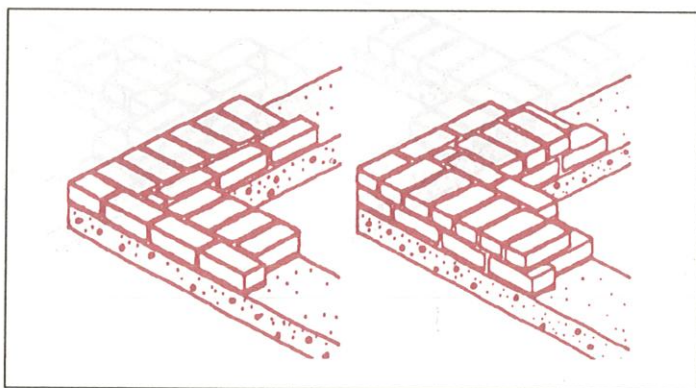
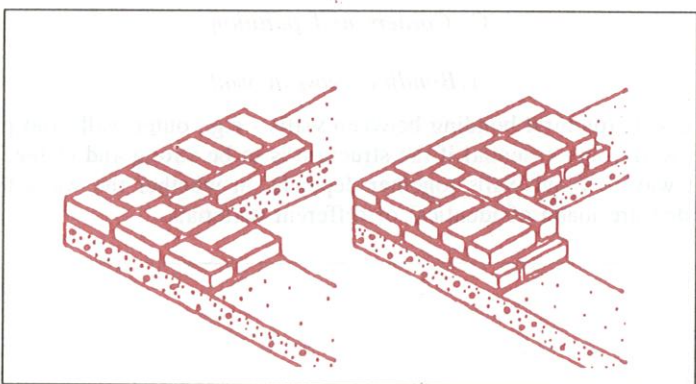
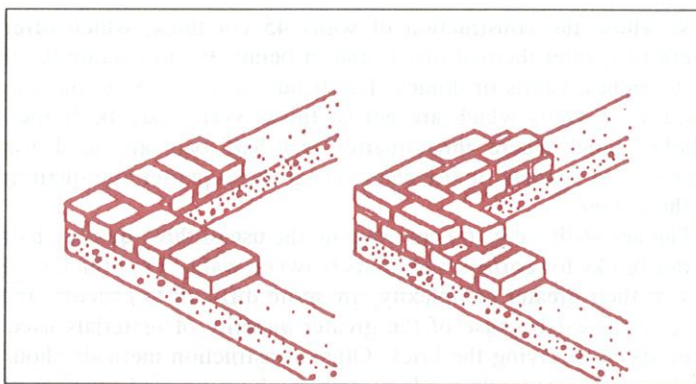


Square elements are often used in adobe construction in South and Central America; typical dimensions are 40 x 40 x 9 cm. Heading bond is most commonly used for these adobes. The corners require the use of a half bat for good toothing; a bigger, rectangular brick helps to prevent weakening of the corner. The same applies to the bonding of outer and partition walls.

### (b) Rectangular bricks



The most commonly used rectangular element, produced by the great majority of presses on the market, has nominal dimensions of



29.5 x 14 x 9 cm. Variations in the thickness of the block do not affect the bond in the chosen bedding plane. This type of brick allows the construction of thin walls only 14 cm thick in stretcher bond, and walls 29.5 cm thick using header bond or stretcher and header bond. A three-quarter bat is required for the construction of right angles. Such



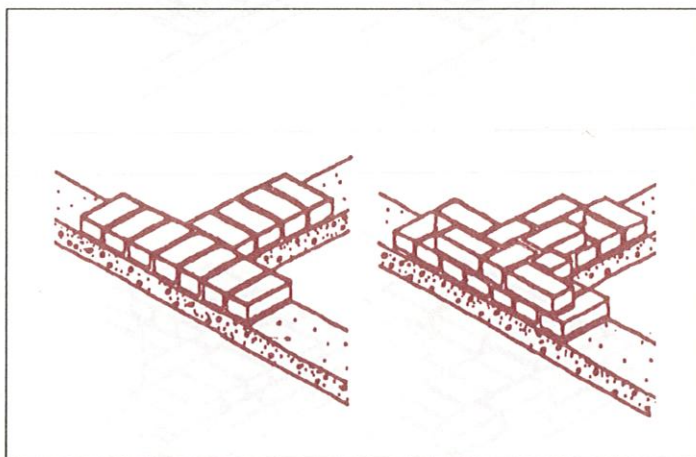
bricks allow the construction of walls 45 cm thick, which offer the benefit of greater thermal inertia and of being able to assume the thrust due to arches, vaults or domes. The bonds in walls 45 cm thick are as varied as in walls which are not so thick. Walls may be header and stretcher bond where three-quarter and half bats are used for the corners or in headers or stretchers, using three-quarter and quarter bats for the corners.

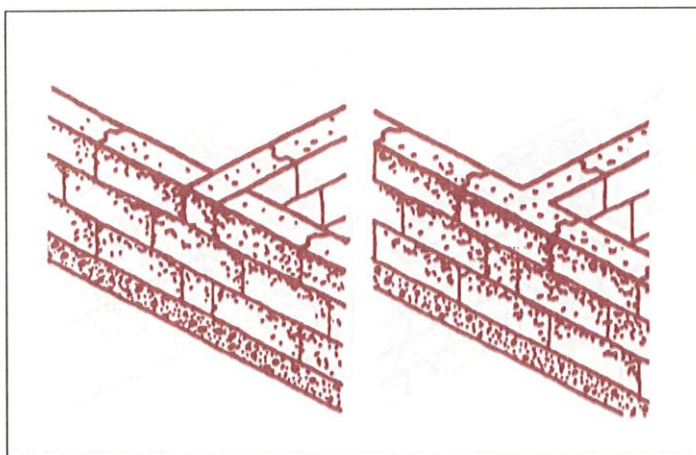
Thicker walls - e.g., 60 cm - require the use of three-quarter, half and quarter bricks for corners and joints between walls. Very thick walls, in view of their greater complexity, are more difficult to execute, and are less economical because of the greater quantity of materials used and lower speed of laying the brick. Other construction methods should be sought for thicker walls in plain earth, such as rammed earth or cob.

### *C. Corners and partitions*

#### *1. Bonding between walls*

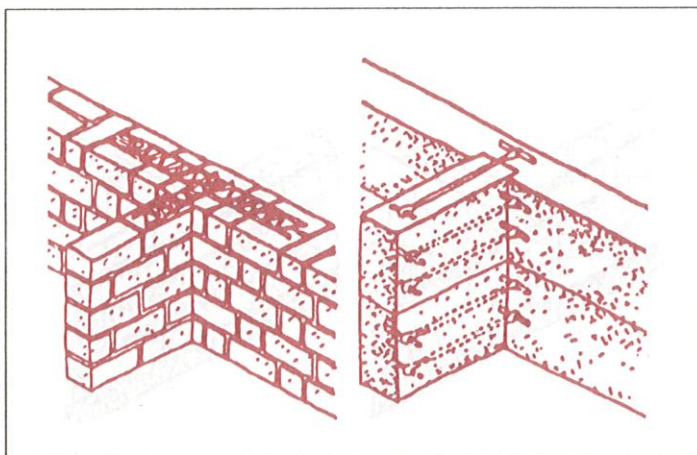
Good structural bonding between walls - e.g., outer walls and partition walls - are essential if the structure is to be strong and stable. The best way to bond walls together depends on whether the walls to be bonded are made of identical or different materials.





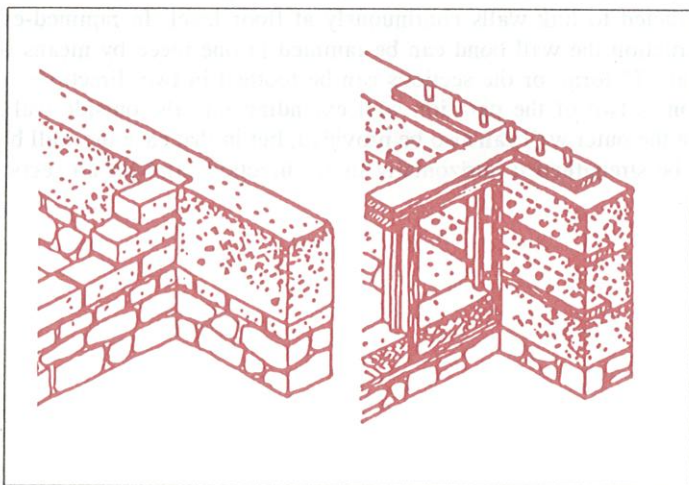
In brickwork and blockwork, the bond between walls should be perfect, in order to ensure good toothing. Wall bonds must be designed in accordance with the rules of masonry bond and the overlap must be adequate, with a view to preventing vertical cracking through the perpends. The complexity of the bond between walls depends on their thickness, and the use of three-quarter bats and half bats is fairly common.

Where a thick wall and a thin wall are to be bonded a vertical groove in the thick wall can be provided into which the thin wall can be fitted. Horizontal strengthening must, however, also be provided (bars, wood, netting). These strengthen the "T" bond between the walls, which may be installed every fifth or sixth course of bricks. Ties should also be constructed to link walls continuously at floor level. In rammed-earth construction the wall bond can be rammed in one piece by means of a special "T" form, or the sections can be toothed in two directions: one section in two of the partition wall extending into the outside wall. A slot in the outer wall can also be provided, but in that case the wall bond must be strengthened horizontally in all directions and for all sections.



In cases where different materials are used toothed wall bonds are not recommended since the difference in function and strength of the materials could cause cracking. The best procedure is thus to make a slot in the thicker wall. For bonding light wooden-frame dividing walls to rammed-earth walls, the best course is to embed boards in the rammed earth and to screw the dividing wall to the boards. The last wooden post for the partition can also be sunk into the wall.

## 2. Corners

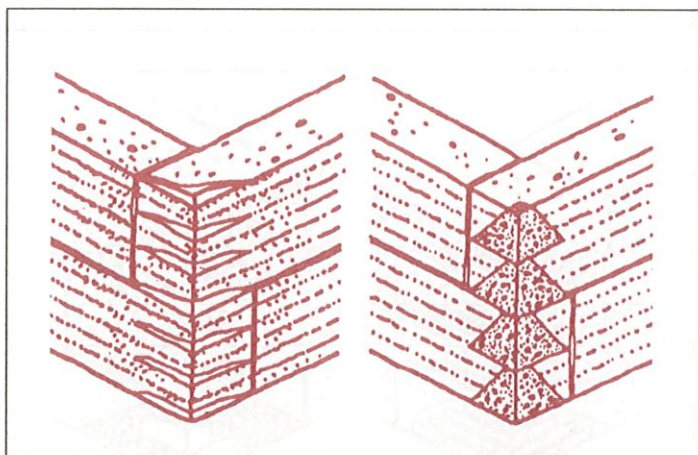




The stability of the corners is largely responsible for the stability of the structure. It is usually in the corners of earth houses that structural cracks which jeopardize the structure can be observed. These cracks may be caused by the different rates of settlement of the ground and the structure (in the case of poor foundations) and it is thus the corners which suffer most as well as the other wall bonds. Such fissures, however, may also be the result of poor bonding between the walls.

(a) *Corners in earth*

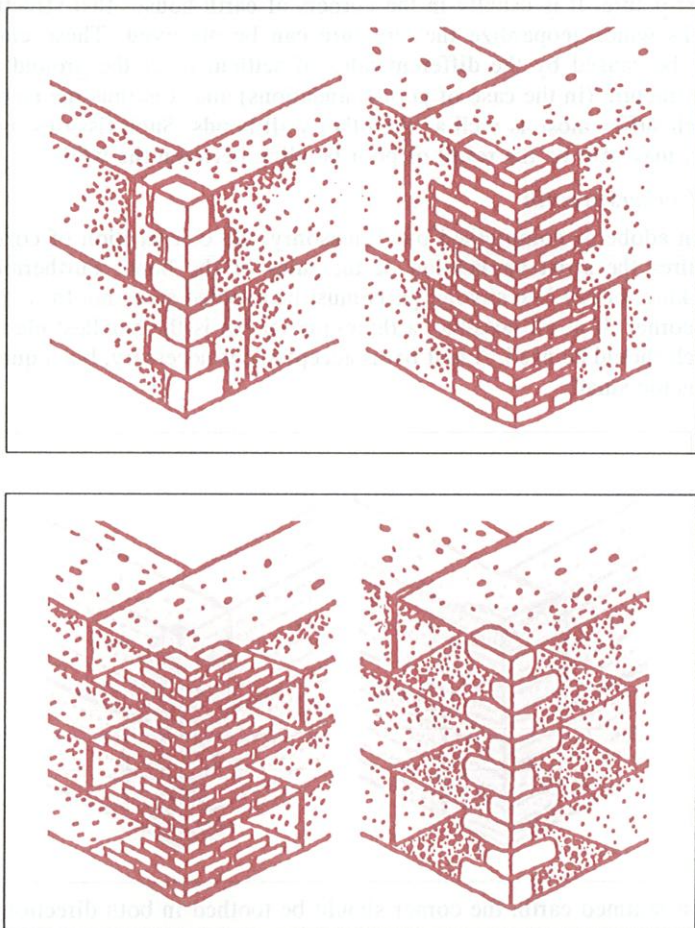
In adobe or compressed block masonry, the construction of corners requires the strict application of the rules of the bond. Furthermore, breaking bricks into smaller parts must be avoided so as not to weaken the corner. If at all possible, a three-quarter bat is the smallest element which should be used. A half bat is acceptable if necessary, but a quarter bat is too small.



In rammed earth, the corner should be toothed in both directions of the wall being bonded, or, alternatively, every other section can be toothed. The corner can be formed in a single piece with a special L-shaped form, and in this case care must be taken to ensure that the displacement of the cross joints is great enough between sections. Do not neglect to bevel corners.

In cob construction there are numerous examples of thickened corners. These are very acceptable and constitute a form of wearing layer.

(b) *Corners in hard materials*



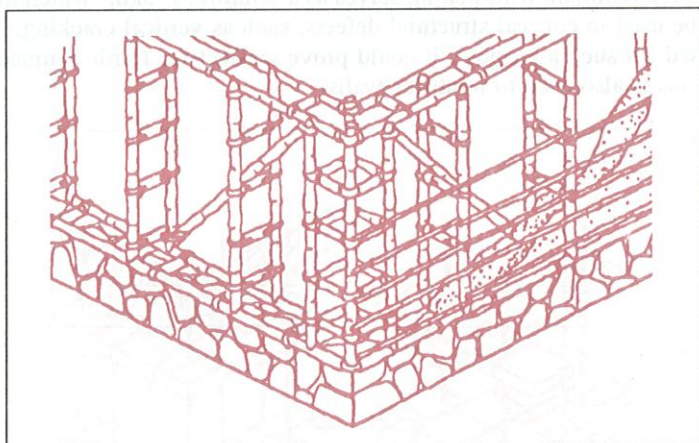
There are numerous methods of strengthening corners. These involve the use of stone, burnt brick, or the use of lime or cement mortar. These materials are included in the outer corners which are exposed to

erosion. They are placed in the form (in the case of rammed earth) as the earth is being rammed. The corners take the form of rectangular or triangular toothing to ensure good bonding between the "hard" material and the soil. A layer of mortar between the two materials enhances their bonding. The strengthening of corners with layers of mortar must be carried out carefully and uniformly.

#### *D. Reinforcements and bondbeams*

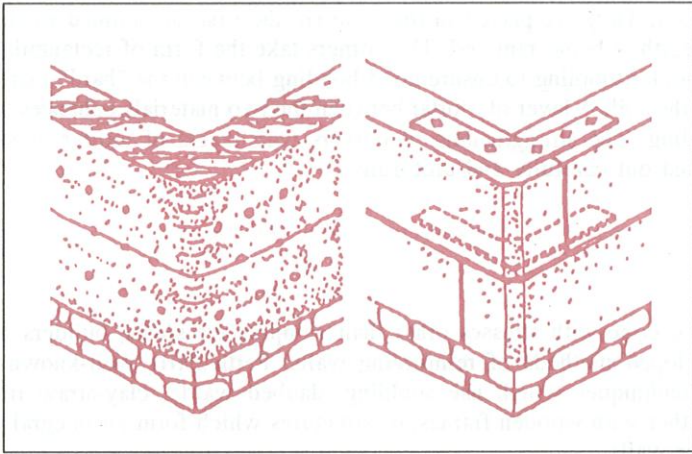
##### *1. Strengthened walls*

To cope with stresses other than compressive stress, builders have developed methods of reinforcing walls. Particularly well-known are the techniques which use studding, daubed wattle, clay-straw infills together with wooden frames, or structures which form an integral part of the walls.

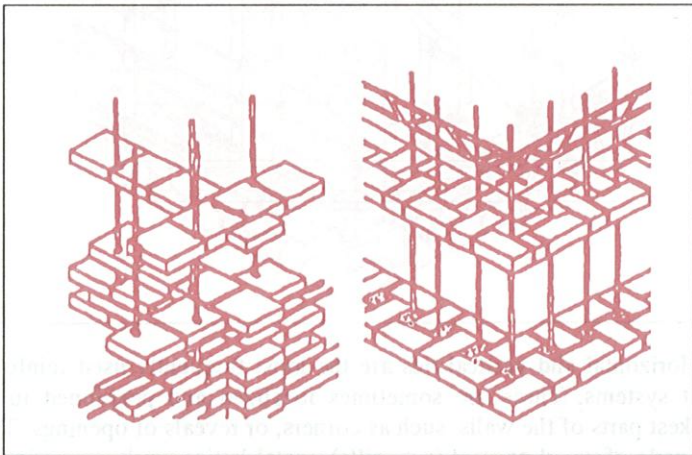


Horizontal and vertical ties are the most frequently used reinforcement systems. These are sometimes localized and positioned in the weakest parts of the walls, such as corners, or reveals of openings. They are made of wood or steel (e.g., sills), metal lattice work, or netting (in corners).





A rendering on wire-netting serves as a reinforced "skin" which must not be used to conceal structural defects, such as vertical cracking. If it is used for such a purpose, it could prove ineffective. Earth rammed in gabions is also used to reinforce walls.



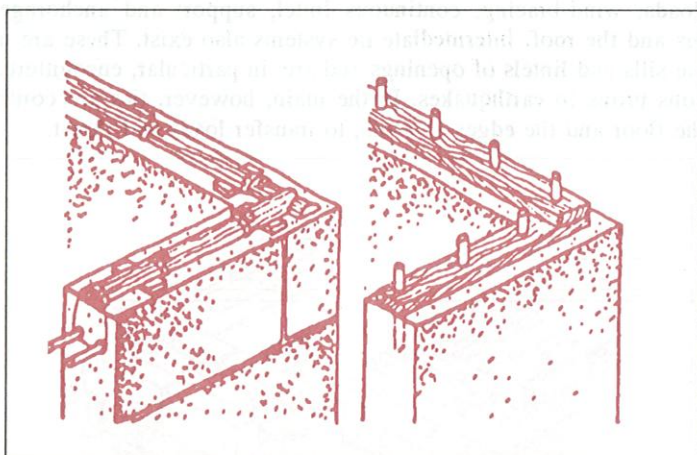
For thin walls (29.5 x 14 x 9 cm bricks in stretcher bond), the use of buttresses integrated into facades around door and window openings can be considered (simple abutment outwards). The walls are also tied

horizontally at floor or roof level. For gable ends, a pillar should be integrated in the axis of wall, worked into the bond and properly toothed into the wall. This pillar stiffens the wall, provides better resistance to wind loading and takes up the load of the ridgepole. Ties at the base of the gable transmit the thrust from the roof.

## 2. Ring beams

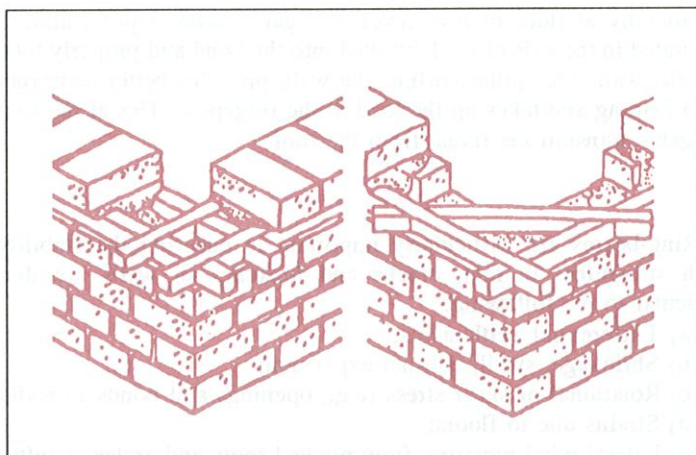
Ring-beams are particularly important in ensuring the stability of earth structures. In fact, cracks and breaches in walls are due in particular to the following:

- (a) Differential settlements;
- (b) Shrinkage, swell, thermal expansion;
- (c) Rotational or shear stress (e.g., openings and bonds in walls);
- (d) Strains due to floors;
- (e) Lateral wind pressure, from pitched roofs and arches, vaults and domes.

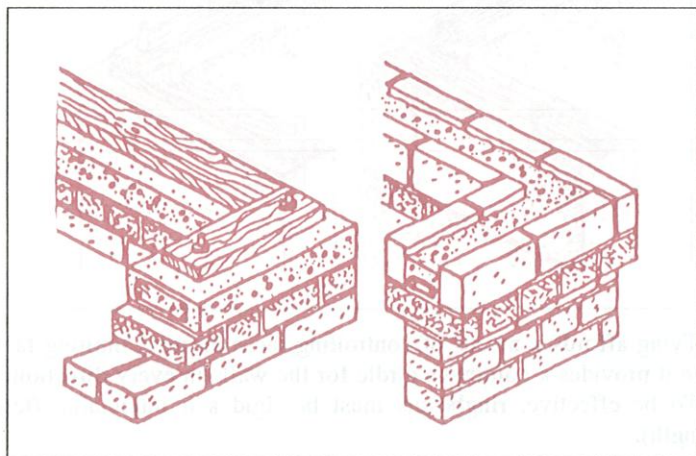


Tying affords a means of controlling these harmful limiting factors since it provides a continuous girdle for the walls in every direction.

To be effective, ringbeams must be rigid and unyielding (tensile strength).



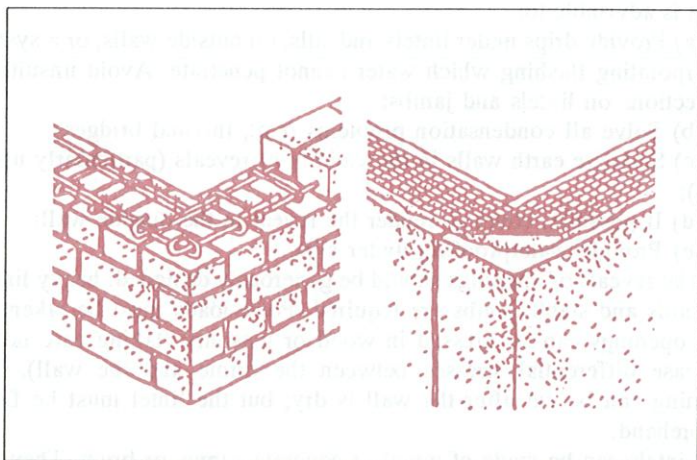
Ringbeams can be used for other purposes, such as even distribution of loads, wind-bracing, continuous lintel, support and anchorage of floors and the roof. Intermediate tie systems also exist. These are used in the sills and lintels of openings and are, in particular, encountered in regions prone to earthquakes. In the main, however, ties are confined to the floor and the edges of roofs, to transfer loads and thrust.



The main materials used are wood, steel and concrete. These materials must have a high degree of adhesion with the soil in order to



ensure the effectiveness of the tie. Wooden ringbeams are often set in the thickness of walls, after immersion in mortar or anchored by means of steel or metal collars. Economic and quite effective solutions consist of using local wood such as bamboo or eucalyptus. Wood is prone to water and fire damage and damage by termites if it is not specially treated. It is desirable to use treated and dry wood from which the has been stripped.



Steel ties must be fastened properly, especially at the angles of walls and adequately coated with mortar and concrete. Metal lattice ties also exist. It is advisable to cast the tie in reinforced concrete upon a layer of stabilized earth in order to ensure that the concrete adheres well to the earth and that there is no deterioration due to contact with wet material.

## IV. OPENINGS

### *A. Basic principles*

The structural bond between the frames of openings and earth walls must be given particular attention to avoid cracking, which would give rise to rapid erosion, especially if there is the added problem of chronic dampness.

It is advisable to:

(a) Provide drips under lintels and sills, on outside walls, or a system incorporating flashing which water cannot penetrate. Avoid unsuitable projections on lintels and jambs;

(b) Solve all condensation problems (e.g., thermal bridges);

(c) Stabilize earth walls in the vicinity of reveals (particularly under sills);

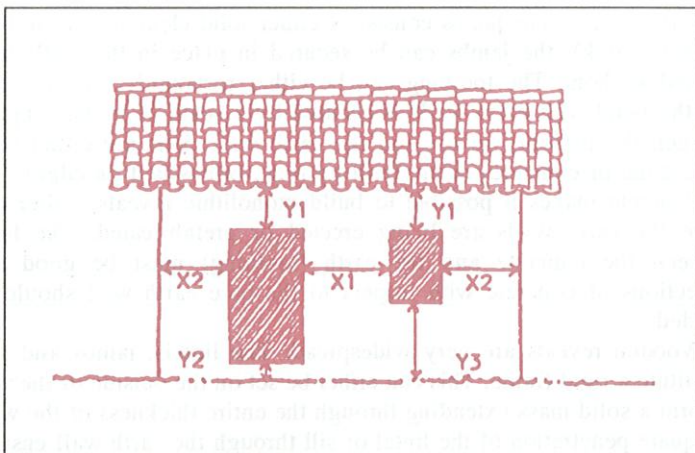
(d) If possible, cover or render the reveal in the outside wall;

(e) Provide waterproofing under sills.

The reveals of openings should be generously designed: heavy lintels and sills and stable jambs are required. Point loads must be taken up. The openings can be dressed in wood or masonry (taking care not to increase differential stresses between the frame and the wall). The opening can be cut after the wall is dry, but the lintel must be fitted beforehand.

Lintels can be made of wood or concrete, stone, or brick. They can be cast in situ or prefabricated. Lintels are subject to considerable stress. The lintel must be supported in the wall over at least 25 cm, and more for large openings. It is moreover advisable to increase the compressive strength of supporting lintels: stabilize jambs or dress them in masonry. In designing sills, loads transmitted by the jambs must be properly taken up. Lengthen the sill and add reinforcement under the sill. To prevent shearing of the window breast, it is best to use dry joints between the breast-wall and the wall proper or else use independent infilling after the construction of the wall: e.g., rammed-earth wall, sun-dried brick breast-wall. Plug the dry joints of the breast-wall once the wall has completely dried and is stable.

The following rules are vernacular guidelines, and do not exclude variations in the design of openings.



(a) The ratio of apertures to solid sections in any one wall should not be greater than 1:3 and should be as evenly distributed as possible. Avoid concentrations of apertures or excessively large openings.

(b) The total length of the openings should not be more than 35 per cent of the length of the wall.

(c) Conventional spans should not exceed 1.20 m.

(d) The minimum distance between an opening and a corner is 1 m.

(e) The width of a pier should not be less than the thickness of the wall with a minimum of 65 cm. Piers less than 1 m wide cannot bear loads.

(f) The ratio of the height of the breast-walling under sills and above lintels to the width of the bay should be adequate.

### *B. Basic details*

The reveals of openings can be dressed with "hard" materials so as to ensure that loads and stresses are properly taken up. This procedure facilitates the anchoring or fixing of joinery, but the provision of such hardening is difficult: a problem of the bond between "hard" materials and earth walls.

Stone or brick lintels can be in the form of straight lintels or a lintel course, or variously shaped arches: dropped, segmental, basket-handle,

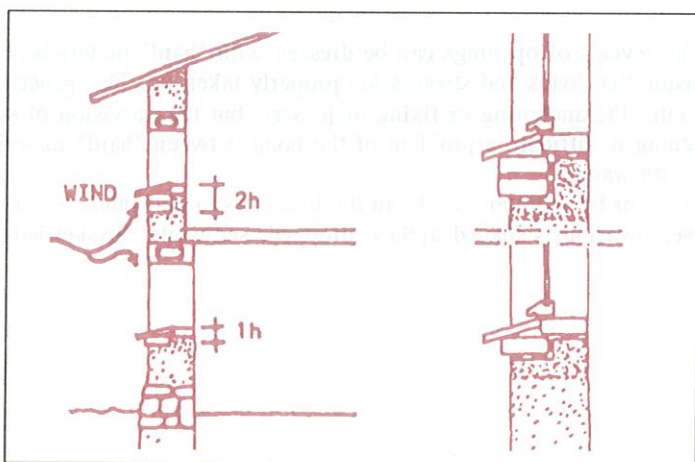


semicircular etc. The jambs consist of either solid elements or are built up (e.g., brick); the jambs can be secured in place in the walls with toothed anchors. The toothing can be either rectangular or triangular and the bond with earth walls is secured by a seam of mortar applied between the masonry reveal and the earth wall. Sills are either solid (e.g., stone or concrete) or are built up (e.g., bricks laid on edge).

Concrete makes it possible to build monolithic reveals, either cast while the earth walls are being erected or prefabricated. The bond between the concrete and the earth (toothing) must be good and projections of concrete with respect to the bare earth wall should be avoided.

Wooden reveals are very widespread. The lintels, jambs and sills constitute a rigid frame. This can either be set on the outside of the wall or form a solid mass extending through the entire thickness of the wall. Adequate penetration of the lintel or sill through the earth wall ensures good structural bonding of the materials. Nevertheless, it is advisable to place boards on a mortar bed or even on brickwork. In regions with a damp climate it is better to render these wooden frames (roughing or studding of wood) and provide flashing above the lintel.

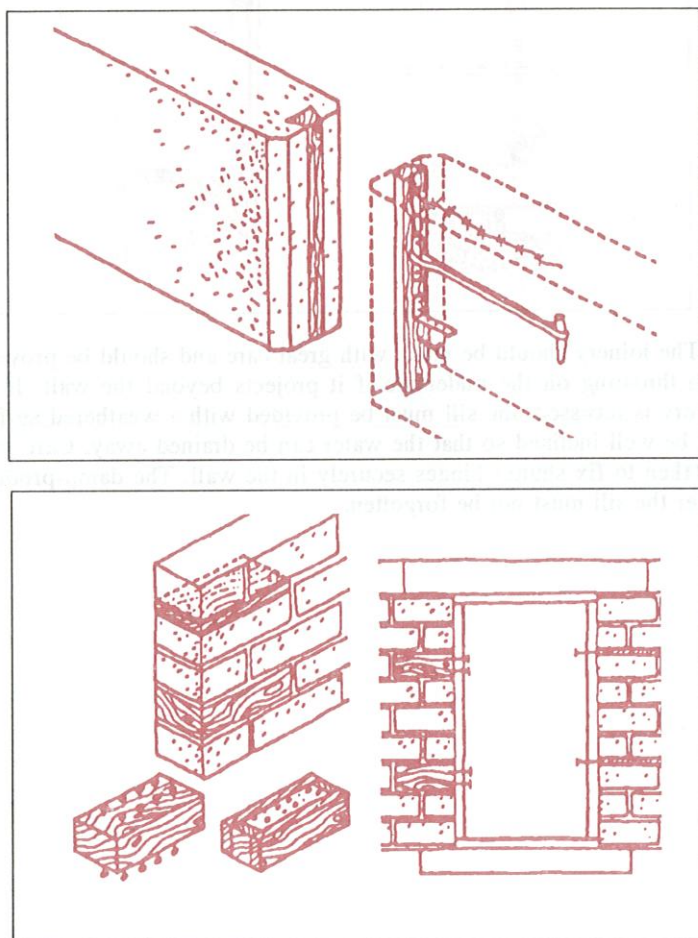
Reveals can be made of stabilized earth or be strengthened. In walls made of stabilized compressed blocks the lintel can be replaced by a brick arch. The jambs must be perfectly bonded while the breast-wall can be independent, constructed after the walls and arches. Small openings can be of corbelled construction, if carefully bonded. In rammed-earth walls the lintel can be made of wood or be a brick arch and the jambs reinforced by lime mortar beds or triangular toothing in mortar. Care must be taken to bevel projecting angles so as to reduce erosion.



Reveals should be protected against water and wind erosion. This can be very pronounced on a wall subject to cracking. Such protection

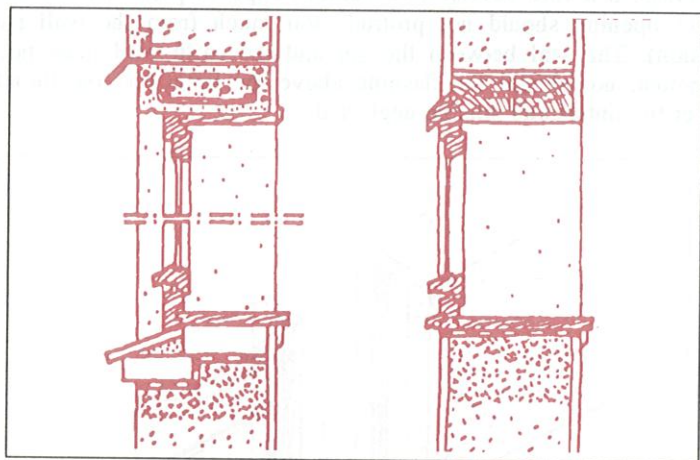
can be provided by giving careful attention to the construction of reveals. It can, moreover, be enhanced by surface stabilization or rendering round the reveals.

For dwellings with storeys above ground level, openings on walls facing the prevailing winds are more exposed than on the ground floor, particularly at sill level. The breaking wind creates eddies which are particularly marked near window breasts and lintels of ground floor openings. It is thus advisable to stabilize exposed parts. The sill of the upper opening should not protrude too much from the wall (wind erosion). The seal between the sill and the earth wall must not be forgotten, nor should the flashing above the lintel and the throating under the lintels and sills be neglected.



When it is planned to fix subframes, for windows and doors directly in earth walls, care must be taken to provide solid anchoring as the

shocks and vibration resulting from frequent use can cause cracking and loosening. Pieces of wood, to which the joinery can be attached, can be embedded into the earth walls. The fastening of these boards (planks in the form of jambs or special blocks) is done by means of metal holdfasts, by nailing and setting after coating in mortar, or by means of barbed wire ties which are progressively sunk into the wall as the jambs are built.



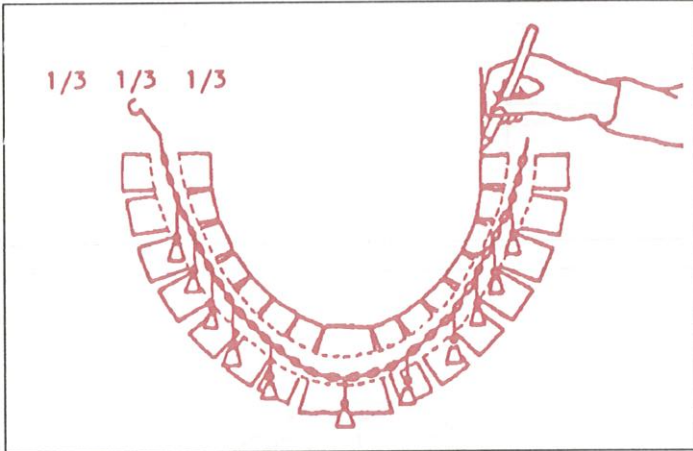
The joinery should be made with great care and should be provided with throating on the underside if it projects beyond the wall. If the joinery is recessed, the sill must be provided with a weathered surface and be well inclined so that the water can be drained away. Care must be taken to fix shutter hinges securely in the wall. The damp-proofing under the sill must not be forgotten.



## C. Arches

### 1. Arch design

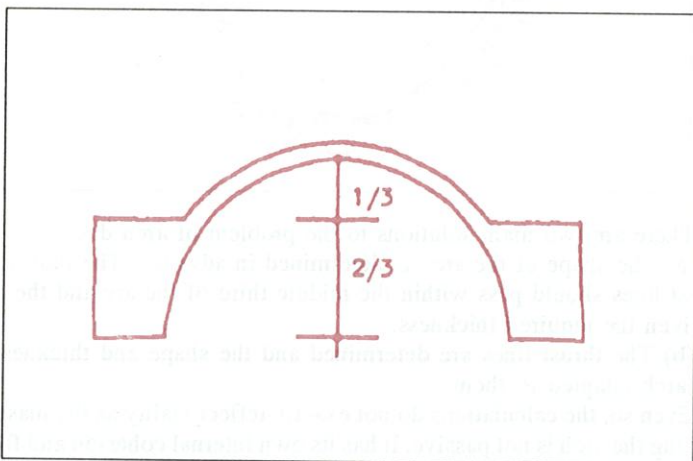
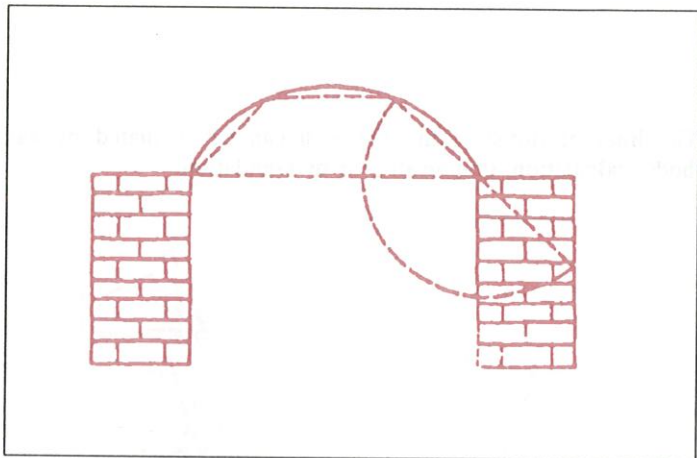
The lines of thrust within the arch can be evaluated by various methods: calculation, graphically, or by simulation.



There are two main solutions to the problem of arch design:

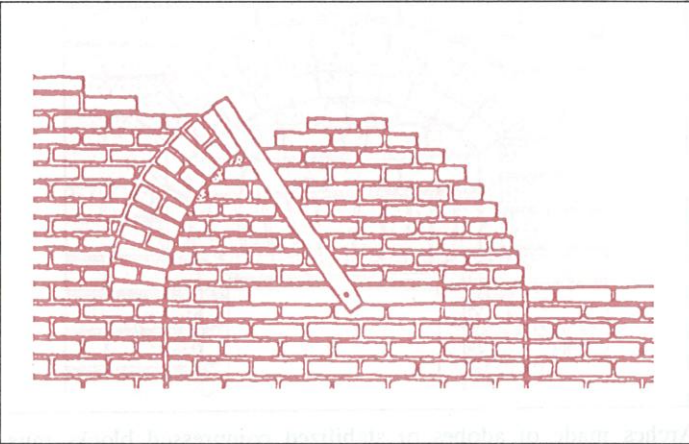
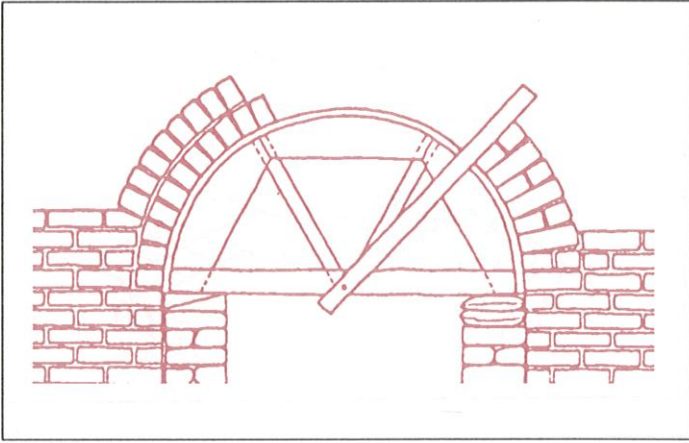
- (a) The shape of the arch is determined in advance. The plot of the thrust lines should pass within the middle third of the arc and the arch is given the required thickness.
- (b) The thrust lines are determined and the shape and thickness of the arch adapted to them.

Even so, the calculations do not exactly reflect reality as the masonry loading the arch is not passive. It has its own internal cohesion and forms a corbelled arch (this can be observed in walls which have collapsed, and the span may be as much as 7 m). Any plot of thrust lines is therefore hypothetical. It is thus essential, especially for large spans, to build the arches with great care to avoid cracking and loosening.



Arches transmit great thrust onto the supporting points and on to the piers supporting these. Consequently, the latter must be solid and stable. These thrusts can be calculated or estimated graphically (e.g., the Maxwell-Cremona polygon of forces). It is also possible to estimate the size of piers by an empirical method: the prolongation of the first third if the arch should always fall within the pier. When two arches having the same plot meet on the same pier, the thrusts cancel one another out. In this case, only the descending vertical load is considered.

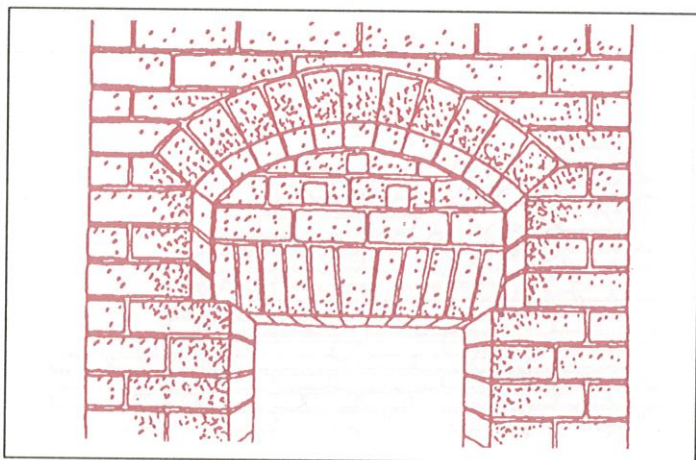
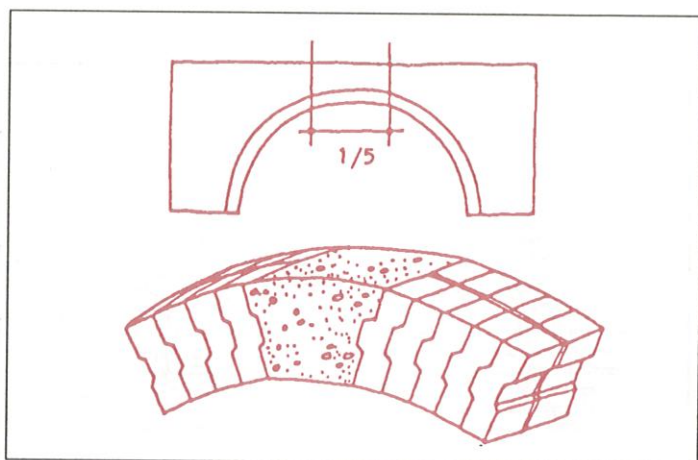
## 2. Building arches



Depending on the span and loads involved, arches may be built using a single, double or triple ring. A light formwork permits the construction of the first ring, which serves in turn as a base for the second, and so on. However, the load distribution of these consecutive rings must be correct, and they must be bonded to one another so that no cracking occurs. The actual construction of the bond is a more delicate task.

A corbelled arch requires no formwork (with a shape approaching that of an oggee arch) but other sorts require the support of formwork. The formwork can be wood or metal, temporary masonry or something even lighter (e.g., formwork made from palm trunks with a coat of rendering). The use of wedged wooden blocks or small sandbags, allows the formwork to be removed without stressing the arch (risk of cracking).





Arches made of adobes or stabilized compressed blocks must be well bonded: the heads of the joints between the masonry and the arch must correspond. Construction proceeds symmetrically from the two

imposts of the arch and ending with the keystone. The imposts are recessed in the wall and are cut so as to determine the direction of the arch and to withstand the thrust. In principle the mortar is not taken into account when constructing the arch, the bricks are regarded as if they were laid dry. The bricks touch at the intrados, on the formwork and are wedged at the extrados by a pebble. The packing of the joints must be carried out with great care. Special voussoirs can be used (trapezoidal or interlocking) which prevent slipping. These bricks are better suited to large spans, and the arch and the masonry which it bears are constructed simultaneously. In large arches the keystone is ideally made of a material which is cut to size on the spot and will be quite wide (40 cm). When pebbles are used for wedging, the formwork can be removed immediately. If only mortar is used, it is necessary to allow a drying period before daring to remove the forms.

## V. FLOORS

### A. Ground floors

#### 1. Basic principles

To construct an earth floor, certain rules must be followed and a few precautions taken since the floor must be able to resist perforation, wear, attack by water, standing and moving loads. It should distribute these loads evenly and transmit them to the ground. Furthermore, it may be necessary to enhance the load-bearing capacity of the ground. The floor should also have insulating properties (thermal and acoustic), be easy to maintain, be attractive (texture, colour) and be able to accommodate services (e.g., electricity supply), remain dry and be pest-free.

Earth floors are found mainly in ancillary buildings and spaces such as sheds and outhouses. In cellars, their practicability depends on the permeability of the underlying ground and the level of the groundwater (at least 3 m) and how well the cellar is ventilated. In general, earth floors can be used for dry and well-ventilated spaces, on well-drained and dry soil. They are also used for living areas (e.g., living-room, bedrooms), but this demands very careful finishing and a more elaborate design (e.g., insulation). Their strength, going up to 350 daN/cm<sup>2</sup> for point loads, is high.

Floors and walls function differently. Walls can support heavier loads than those applied to floor slabs. Consequently the floor should be made structurally independent of the walls so as to avoid cracking due to different rates of settlement. The material of the damp-proof membrane against the foundation slab must be flexible so as not to be altered by the different stresses applied by the two structures. The underlying soil upon which the earth floor is laid must be dense enough to avoid settlement. Levelling, backfilling if necessary, and compaction are the required means.

The thickness varies depending on the load-bearing capacity of the underlying ground, the stresses due to the applied loads and the chosen finish. A floor comprising a foundation in pitching, a sand layer and covered by rammed earth, can be 45 cm thick.

Either the entire floor mass or just the surface layers (more economic) can be stabilized. The same additives are used as for the production of stabilized earth and the procedures are similar. Vegetable glues (e.g., white glue) can also be added. Stabilization considerably enhances the resistance to water and the wear of earth floors.

Dry earth floors are traditionally hardened with animal (horse) urine and ox blood. Ox blood is sprinkled with cinders and clinkers and then beaten. Silicates of soda (floor not completely dry) or fluorosilicates (dry floor) can also be used. Sump oils or a mixture of turpentine and



linseed oil will also serve the purpose. A clean finish can be obtained by using polishing wax.

## *2. Design details*

### *(a) Preparation*

Before constructing an earth floor the underlying ground must be prepared. The layer of earth containing vegetable material and humus is carefully cleared and all organic residues eliminated from it. The upper layer of the earth is rammed except when the soil is subject to swell or when its load-bearing capacity is adequate. The ground must be dry before the floor courses are laid.

### *(b) Waterproofing*

An anticapillary barrier can be made with a 10-cm layer of clayey earth applied in the moist state in carefully rammed layers. Each layer must be dry and fine cracks filled before being covered. The top layer is finished with a flattening hammer after ramming. A bitumen or lime-stabilized sandy soil can replace the clayey soil. Stabilized earth or a plastic sheet can also be used. Whatever solution is adopted, the damp-proof membrane must rise up along the base of the wall.

### *(c) Stone filling*

Dry-stone pitching, 20 to 25 cm deep, makes a good foundation. The largest stones are put down first, followed by tipped gravel. Dry stone can be replaced by gravel and coarse sand or by ballast.

### *(d) Insulation*

The pitching is covered by an insulating layer, which can be a 10-cm layer of clay-straw. If this layer is too weak, it can be covered with a bearing course which could distribute the loads.

### *(e) Load-bearing*

This layer can be made of clayey earth mixed with cut straw or clay-straw containing hard and finely chopped straw (stalks 4 to 6 cm long) to which cement mortar is added, at a rate of one volume of cement for every six volumes of washed sand. The load-bearing layer should be 4 cm thick and always superstabilized so that it will harden after it has cured. Such curing sometimes requires moistening (damp sacks).

### *(f) Finish*

A finish can be made with a thin layer of cement grout to which fine sand is added or which has been given an oil-based treatment. A light filler in the form of sawdust can also be added to the grout. Proportions are as follows: one volume of sand, one volume of cement, one volume of sawdust. To mineralize the sawdust it is soaked beforehand in a lime or cement slurry and dried. The final stage of the finishing can be the colouring or waxing of the floor.

### *(g) Monolithic floors*

Floors can be constructed using standard adobe mortar stabilized with bitumen. First the soil is properly prepared, then the mortar is poured and spread out with a screed after the floor guides have been positioned. Shrinkage cracks must be filled with a finer adobe mortar and the final touches are made with a trowel. After drying, the surface is treated with a mixture of turpentine and linseed oil and allowed to dry for a week before putting down the next layer. The floor can then be waxed and polished.

Earth-stabilized concrete mortar (one part cement to six to eight parts sandy soil) is also suitable. It is put down in a 5-cm thick layer marked out with pegs. Contraction joints must be left every 1.5 m. These must be deep and well defined (3 cm deep and 0.5 cm wide).

Other types of monolithic floors are constructed using rammed earth, sensitive to damp, stabilized rammed earth or rammed stabilized clay-straw. Insulation around the edge and a finishing screed (more costly) can also be provided. These earth floors are not attached to the walls. A flexible joint can be made in clay-straw.

### *(h) Floors made from elements*

Earth-stabilized bricks or tiles can be laid on a 2 cm thick layer of mortar: one part cement to six parts of sandy soil. Care must be taken that the tiles adhere properly to the mortar. The joints can be filled with cement grout. The blocks used should be superstabilized or coated with a wearing layer. These blocks can also be laid on a layer of sand and the joints filled with sand.

## *B. Floors above ground level*

### *1. Basic principles*

The upper surface or covering must be durable, flat, pleasant to look at, easy to maintain and, in the case of flat roofs, watertight.

The structure, woodwork or slab, must be able to support live and dead loads, resist concentrated loads, be very rigid and transmit loads to the supports properly.

The underside, or ceiling must be pleasant to look at.

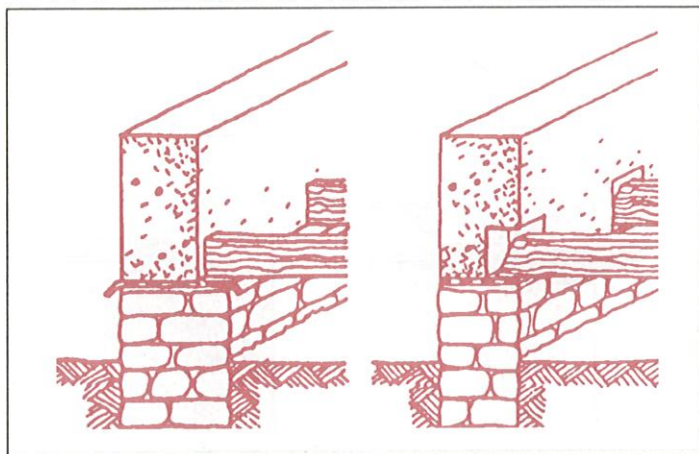
There are various solutions to the problem of the bond between floors and earth walls with support being either independent of the wall or on the wall.

#### *(a) Support independent of the wall*

##### *(i) On the foundations*

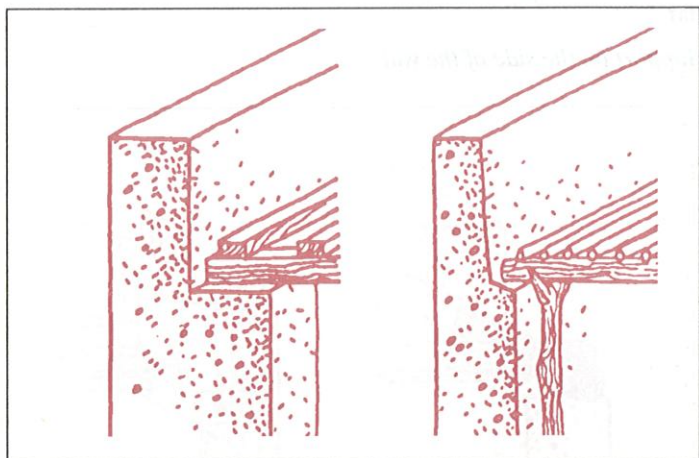
Studs supporting the beams are fixed on notches on the foundation footings. This is satisfactory for floors above cellars or sanitary spaces even though fixing the studs may be difficult.

(ii) On the base course



This is made wider than the wall to take the beams. The base course must be levelled and the beams must not touch the wall. The base course can be widened more cheaply by locating beams in niches in the bottom of the wall, at base course level. Here too the beams must not touch the wall. In both systems a horizontal anticapillary membrane must be laid, and a skirting board fitted as finish. For reinforced-concrete slab floors it is best to use a widened base course since penetration of the wall by the slab will weaken the base of the wall.

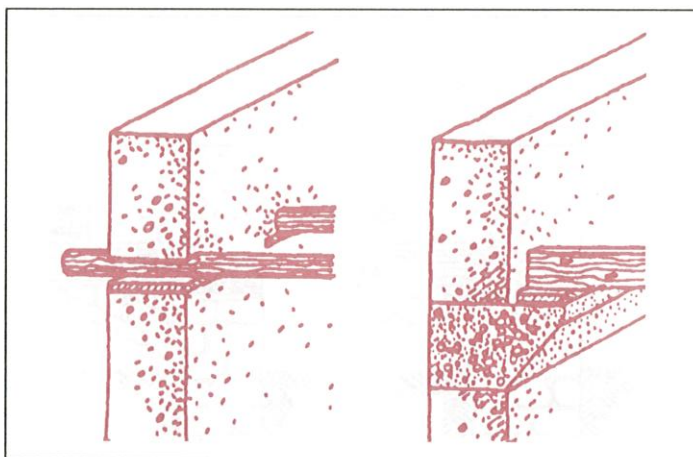
(iii) Beside the wall



This method makes use of wooden corner pieces or masonry projections from the wall. This is the preferred solution for heavy floors and non-load-bearing walls. e.g., wattle filled in with clay-straw or cob.



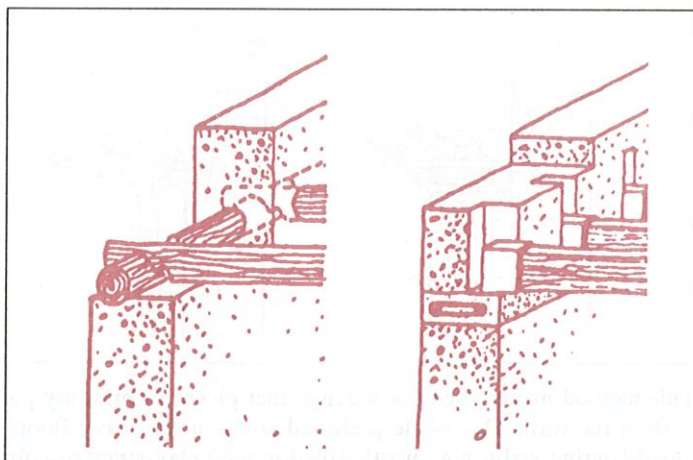
(b) *Support in the wall*



In this system there are the following dangers: concentrated loading (beams) or continuous weakening (slabs) of the wall, rotation of the support (excessive freedom of movement of the beams or sagging of floors), and different degrees of thrust on the wall

Point loads should be distributed by the ring-beam or a carefully designed (weight of loads transferred at an angle of  $45^\circ$ ) wooden, stone or concrete sole plate or through ties. Space for the beams can be hollowed out or provided when building the walls. Treated wood should be used for wooden floors, and contact between wood and earth is to be avoided. Use a flexible material like bitumen, felt or water repellent mortar.

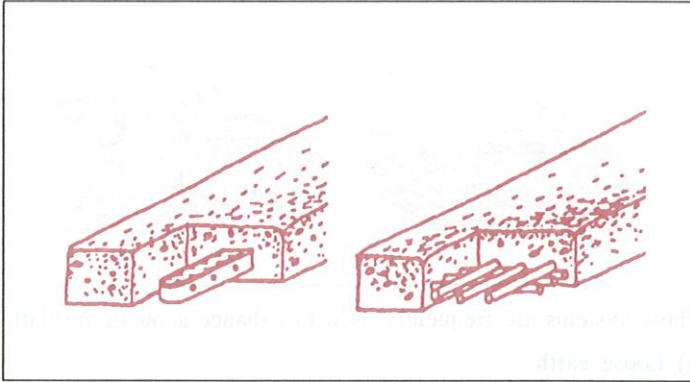
(c) *Support on the side of the wall*



The thickness of the wall is reduced where the floor passes through it. Here, too, care must be taken, with beam supports or a ring-beam should be provided. Avoid placing the floor on a beam along the wall as there is a danger of it being torn out.

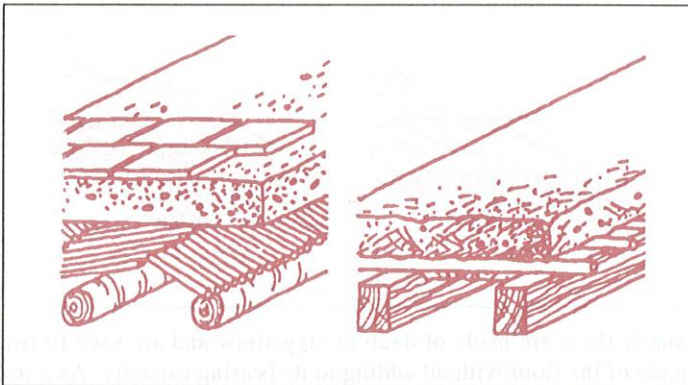
## 2. Design details

### (a) *Earth used for the structure*



The traditional systems in which soil floors reinforced with wood are used have been the object of research aimed at modernization. In the United States, this research has examined bamboo, and in France and Senegal galvanized steel. The results are far from satisfactory as the systems are still very heavy ( $500 \text{ kg/m}^3$ ).

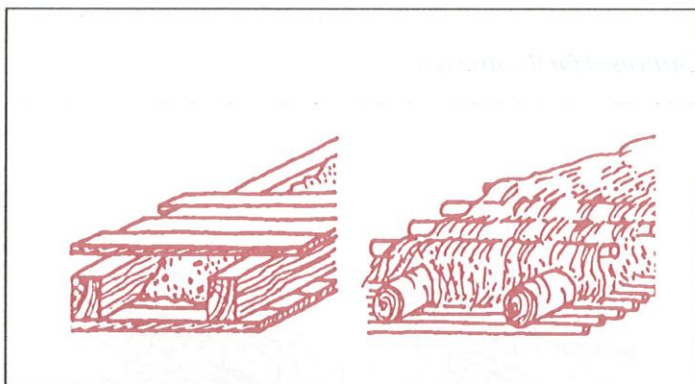
### (b) *Earth used for the surface*



Wooden structures may consist of beams overlaid with boards, wooden logs or sometimes even flat stones. To reduce dust, woven matting, kraft paper, or straw is laid between the support and the earth, which is generally rammed (10 - 15 cm). These floors weigh as much as

250 kg/m<sup>2</sup>. Those laid with packed clay-straw on laths spaced 10 to 15 cm apart are lighter (150 kg/m<sup>2</sup>). The finish is either a stabilized earth-straw wearing layer, or a rendering or even a surface coating.

(c) *Floors with earth infill*

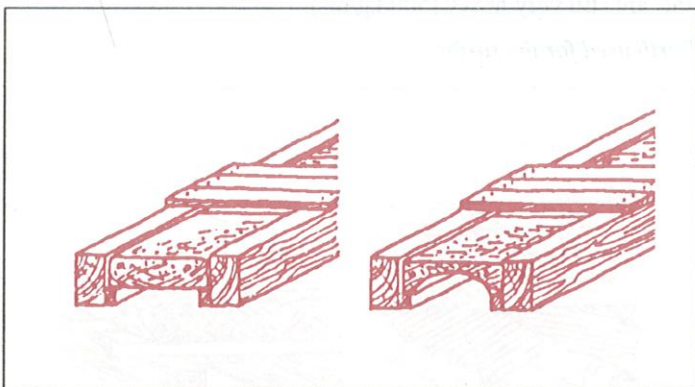


These systems are frequently used to enhance acoustic insulation.

(i) *Loose earth*

Many wood joist floors and wooden board floors, with an underside of boards or reed screen, are packed or pugged with loose soil. The earth used should be absolutely dry.

(ii) *Prefabricated panels*

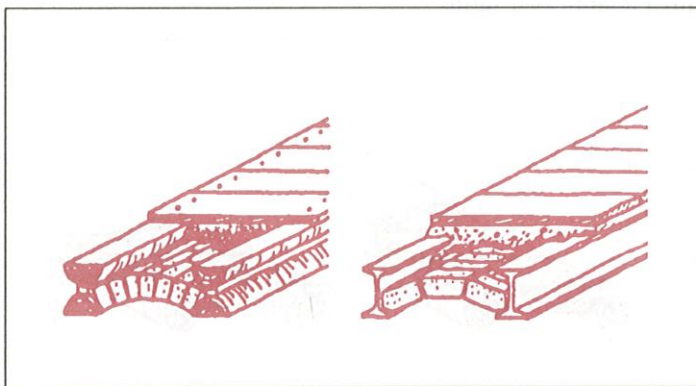


Usually these are made of daub or clay-straw and are used to fill the underside of the floor without adding to its bearing capacity. As a result, the distance between joists/beams can be quite large - 80 to 90 cm and the prefabricated elements can be either short or long: 0.40 to 1.20 m for a thickness of 15 cm and a weight of from 35 kg to 120 kg per element. The shape of the floor cavity makes it possible to lighten the floor.



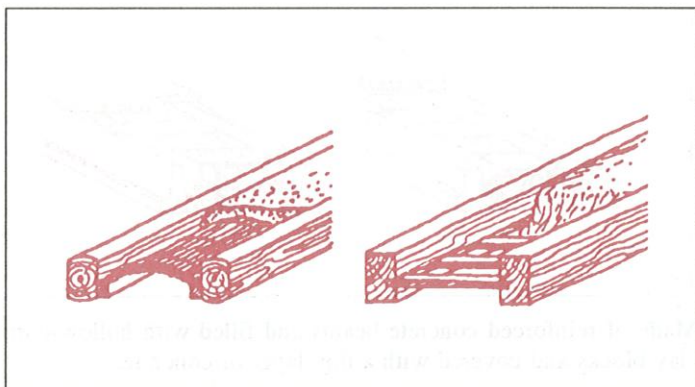
(d) *Vaulting and load-bearing infills*

(i) Earth-brick vaulting



Floors constructed using brick vaulting put the soil in compression with bending stresses being taken up by beams in timber, steel or even reinforced concrete. The space between the beams ranges from 0.5 m for the smaller systems to 2 m for the largest ones, which sometimes require the use of metal ties. The brick vault rests on the lower flanges or the flanks of small beams. These systems are fairly heavy ( $400 \text{ kg/m}^2$ ). They can be constructed with formwork, usually slip forms, with the bricks being laid on edge or flat in two layers and with staggered joints; or without formwork, e.g., in Nubian style slanting bond. Lighter, perforated bricks and tiles, shaped to fit on beams, or procedures which rely on wedging and require no formwork can be used.

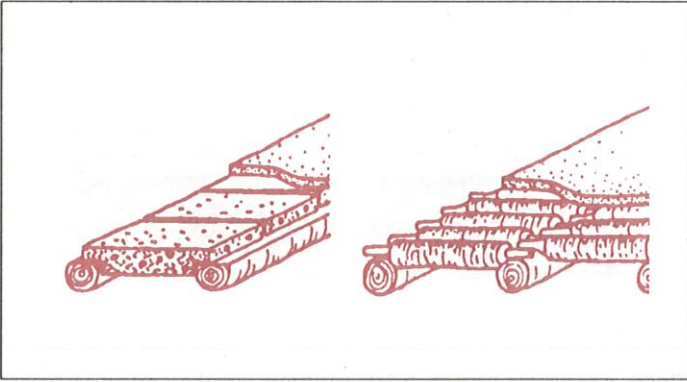
(ii) Cased vaulting



The vaulting is made of clay-straw, and is built using sacrifice formwork in extremely dense reed matting giving a light floor ( $150 \text{ kg/m}^2$ ). Reed is an excellent key for ceiling renderings. Flat vaulting in

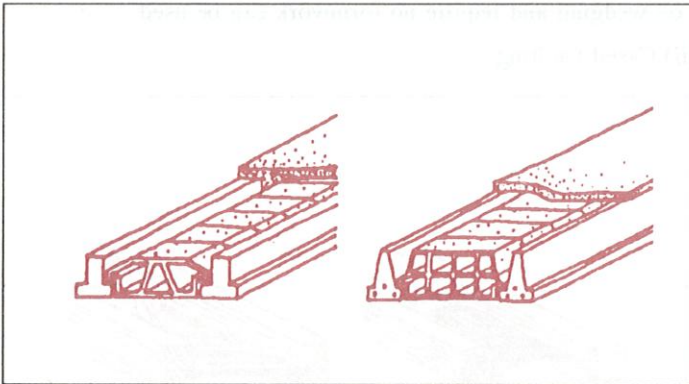
clay-straw internally strengthened with round timbers ( $220 \text{ kg/m}^2$ ). These systems provide good thermal and acoustic insulation.

(iii) Prefabricated infills



The load-bearing element is still a long or short beam, but they are not spaced as far apart from one another ( $0.5 \text{ m}$ ). Clay-straw rough masonry is reinforced by two wooden rods, solving problems of bending. A concrete or even stabilized earth slab ( $6$  to  $10 \text{ cm}$ ) for distributing loads, and which can be reinforced with netting, joins the beams to the infills. Instead of infills, earth reels in straw-clay can be used. These systems are light ( $150$  to  $200 \text{ kg/m}^2$ ).

(iv) Hollow infills



Made of reinforced concrete beams and filled with hollow-concrete on clay blocks and covered with a thin layer of concrete.

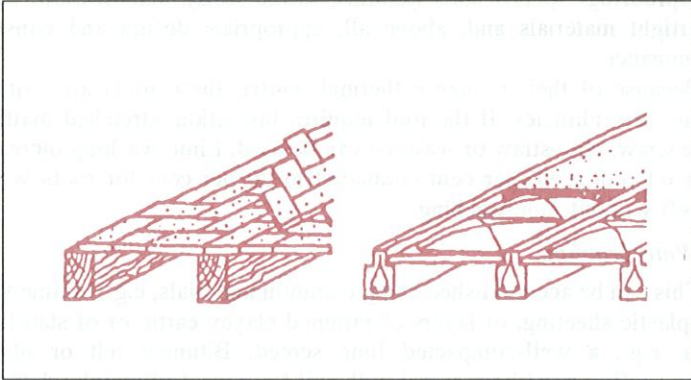
(e) *Other systems*

(i) Hyperbolic infills

These consist of stabilized earth, on short reinforced-concrete beams. They have been tested in Pakistan. Loads can be as high as 1220 kg/m<sup>2</sup>. Research has been conducted in the United States (Max-Pot).

(ii) Thin tiles

These consists of thin superstabilized bricks with a rough-cast plaster finish (two layers).





## VI. ROOFS, VAULTS AND DOMES

### A. Flat roofs

#### 1. Basic principles

Flat earth roofs are very heavy, ranging in weight from  $300 \text{ kg/m}^2$  to as much as  $500 \text{ kg/m}^2$ . They are, therefore, not suitable for use in earthquake-prone regions.

Flat earth roofs are particularly sensitive to water. Torrential rains can destroy a roof. Care must thus be taken to ensure adequate waterproofing: special soils (kaolins, saline soils), stabilization, other watertight materials and, above all, appropriate design and constant maintenance.

Because of their immense thermal inertia, these roofs are suitable for hot, dry climates. If the roof requires insulation, stretched matting, loose straw, clay-straw or seaweed can be used. Lime-washing increases solar reflection: 90 per cent compared to 20 per cent for roofs which are left without lime-washing.

##### (a) Waterproofing

This can be accomplished using common materials, e.g., bitumen felt and plastic sheeting, or layers of rammed clayey earth, or of stabilized earth: e.g., a well-compacted lime screed. Bitumen felt or plastic waterproofing must be covered with soil to prevent ultraviolet damage. Drain water from roofs against the direction of the prevailing wind to prevent splashing. Waterproofing must be assiduously maintained.

##### (b) Gutters and downpipes

Care must be taken not to fix the roof gutters against the walls but instead along the eaves of the roof. Sections should be generous and have a steep enough gradient. Drain water from each section of the roof individually and allow it to escape at the end of a straight gutter. Never use a bend, as there is a danger of overflowing and blocking. Connect roof gutters directly into down pipes.

Use broad sections for downpipes and avoid fixing them against the wall. Do not use fragile or perishable materials (e.g., plastic).

Water should not be discharged at the foot of the wall: provide a rainwater shoe facing towards a drain or gutter. Do not place a rain-water barrel at the foot of the wall. Maintain the downpipes: attend to repairs without delay.

Downpipes built into or recessed into the wall should be avoided. Avoid decorative downpipes and descents: e.g., hanging chains, because of splashing on windy days.

#### 2. Design details

The main drawback of flat earth roofs is that the waterproofing is often defective. In traditional construction, special soils are used:

powdered soil from termite hills (Africa), salt clay mud (the *corak* of Turkey) or soils to which natural stabilizers have been added: e.g., animal dung, shea butter. There are also systems where layers of sand and clay are alternated, to make a thick layer. These roofs are heavy and their watertightness can only be guaranteed if the upper layers become saturated.

The quality of an earth roof depends above all on good execution. Ram the earth in several layers, seal all shrinkage cracks and compact by beating. Pebbles can be tamped into the surface layer. This makes a good wearing layer that is resistant to rain-impact erosion.

It is still preferable to decrease the thickness of the earth (less weight) and to treat or stabilize the soil. Regular maintenance is absolutely essential.

#### (a) *Soil layers*

If these soils are treated or stabilized, effective stabilizers must be used. Stabilization with bitumen is more effective for this type of job than with lime or cement.

#### (b) *Renderings*

A screed of lime and coarse sand, carefully sealed and in which the micro-fissures have been sealed by a regularly refreshed limewash is effective. Rubber-based paints can also be used, but one must be on guard for condensation in damp or poorly ventilated rooms.

#### (c) *Bitumen felt*

This can be placed under rammed earth which is then covered with pebbles and planted moss. It can also be fitted above the rammed earth but must be protected against heat with gravel. The connections with parapets and gutters must be carefully maintained.

#### (d) *Plastic sheet*

A polyethylene sheet under the soil is just as effective as bitumen felt. The soil can be sown with grass with non-penetrating roots. The joints between the roof and the walls must be made with care.

#### (e) *Paving, tiles, flags*

Accessible roofs can be paved with all sorts of surfaces. The gradient must be steep enough to allow water to be effectively drained towards gargoyles and downpipes. Use a water-repellent mortar.

#### (f) *Roof overhang*

The function of a roof overhang is manifold: to retain the soil of which the roof is made, to decrease erosion at the top of the wall, to discharge water away from the base of the wall, to protect the surface of the wall against rain, and to provide shade.

Wide eaves (at least 30 cm) are often encountered in traditional earth architecture. They provide greater stability and resistance to

pressure differences caused by the wind. Such eaves can be fitted with gutters of generous proportions. These should be firmly fastened.

#### (g) *Parapets*

A parapet allows the roofing soil to be retained and gives greater control over the drainage of water from the roof by guiding the water to the gargoyles and downpipes. A parapet also serves as a railing for accessible terraces and affords effective protection against pressure differences due to wind. In addition, the parapet plays an aesthetic role. It should be heavy and constructed of durable materials and/or protected from erosion either by a coping (30 cm minimum) made of a conventional material (stone, brick, tile, reeds and earth) or by rendering, preferably waterproof. The upstands of damp-proofing against the parapet and around gargoyles should be very carefully constructed.

### *B. Pitched roofs*

#### *1. Basic principles*

Pitched roofs with broad eaves (minimum 30 cm) drain rainwater very well and are particularly well suited to earth structures. These roofs are also suitable for use in tropical cyclone regions (minimum gradient,  $30^\circ$ ). This applies, in particular, to hipped roofs (i.e., four slopes) which are preferable in such regions to gable roofs (two slopes).

Hipped roofs offer better protection against wind and rain and economize on wall material, but make the structure more complicated. These elaborate roofs are costly in materials and labour and it is not unusual to see that the pitch is reduced. This reduces the surface area and economizes on the roof frame and decking.

Hipped and gable roofs make it possible to build "umbrella" and "parasol" structures erected before raising the walls and enabling the work to be carried out in a sheltered area. This system does away with the limitations of load and thrust on earth walls since the roof structure bears directly on the foundations and slabs. There is, however, a redundancy of structure and materials which are acceptable only in richer economies or in large construction projects.

The roof must be built rapidly and not too long after the rest of the construction work. If it rains during the construction of the roof, the top of the exposed walls must be well protected. One must always allow for the possible failure of the roof and make the top of the walls watertight.

There is a suitable pitch for every roof covering. Reducing this pitch may lead to leaks as the result of inadequate drainage, standing water or infiltration by water.

Saw-tooth roofs are to be avoided as are roofs with two adjacent slopes having low edges, unless the use of wide sloping gutters is envisaged.

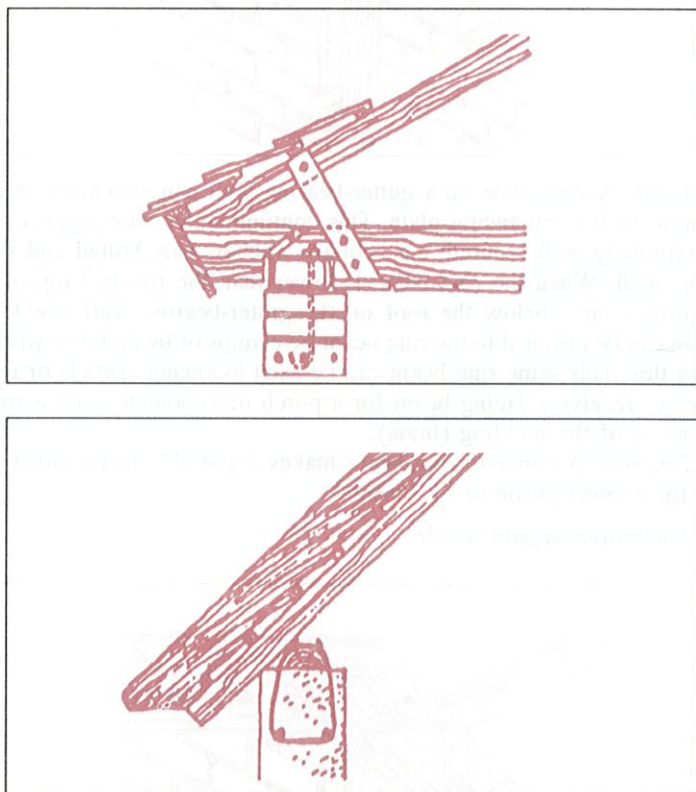
The joints of damp-proofing must be properly executed.



Walls of which the upper portion forms a gable are to be avoided as they make flashing and mortar infilling necessary and this is not always reliable. The flashing for roofs supported by gable walls should be executed by means of a strip of rendering or wearing surface consisting of stones or burnt bricks which affords protection against water splash.

Horizontal thrust must either be eliminated or properly taken up: there is a danger of walls bending or of cracks around openings. Loads should be uniformly distributed on ring beams. Reinforce gables of structures with thin walls: reinforcement, ties, posts.

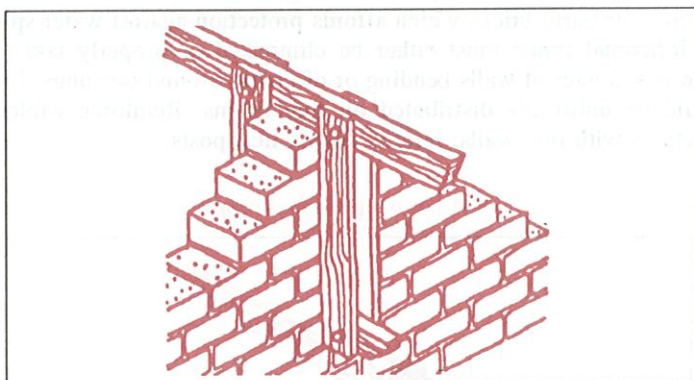
## *2. Anchoring pitched roofs*



Anchoring roofs to walls is absolutely essential if the danger of causing deformation of the roofing and roof-loss in strong winds is to be avoided. This precaution is of cardinal importance in regions prone to tropical cyclones. As a general rule, the anchoring system must be very solid and properly designed. No economies on materials are justified. The roof must be fastened to outside walls, gutter-bearing walls and gable walls, but can also be anchored to dividing walls. If the structure of the building is reinforced with concrete or wooden posts,

anchoring is fairly easy. It is, however, better to anchor roofs on continuous ties than on isolated supports.

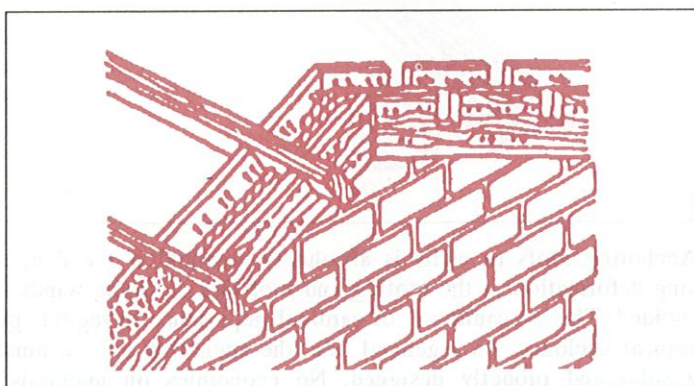
(a) *Anchoring on gutter-bearing walls*

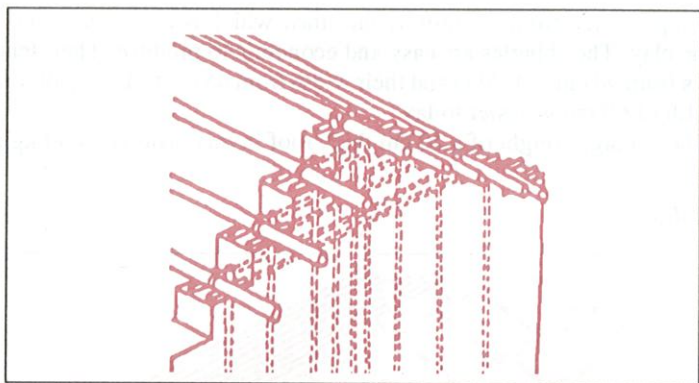


**Wood.** A wall plate on a gutter-bearing wall can also act as a ring beam as well as an anchor plate. This continuous wooden support must be extremely well secured: e.g., collars, anchor-bars bolted and fixed to the wall. When the ring beam is lower than the finished top of the levelling course below the roof on the gutter-bearing wall, the lower purlin can be fastened to the ring beam by clamps or by metal or wooden beam ties. This same ring beam can be used to anchor corbels or metal shoes to receive a facing beam for a porch or verandah, even a future extension of the building (India).

**Concrete.** A concrete ring beam makes it possible to provide iron ties for a lower purlin or roof beam.

(b) *Anchorage on gable walls*

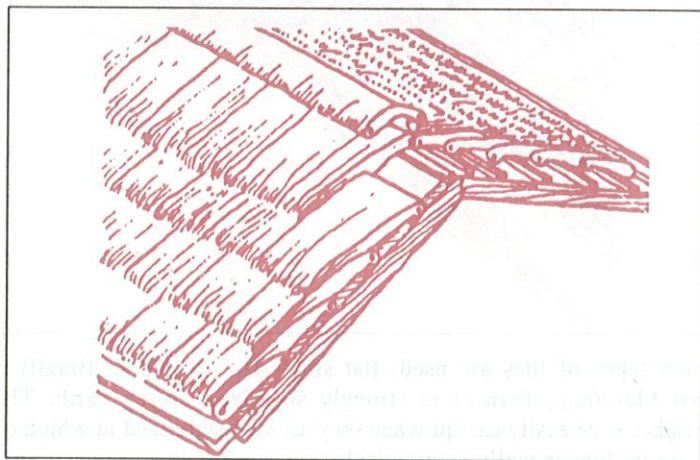




Hipped roofs are anchored to side walls in accordance with the principles already set forth. For gable roofs with purlins extending into the gables, the purlins can be anchored to the ring beam, which is an extension of the one in the gutter-bearing walls or an alternative ring beam at the height of the support of the purlins. Metal or wooden tie bars fixed to wooden corbels at the level of the ring beam can also be used, either above it (the weight bears on the ties) or below it (tensile stresses due to wind are exerted on the ring beam). This solution to the problem of anchoring to the ring beam avoids overloading the gable itself, which is the weakest wall in the structure. Systems incorporating clamps or wooden or metal ties increase the stiffness of the gable.

### 3. Design details

#### (a) Clay-strawshingles



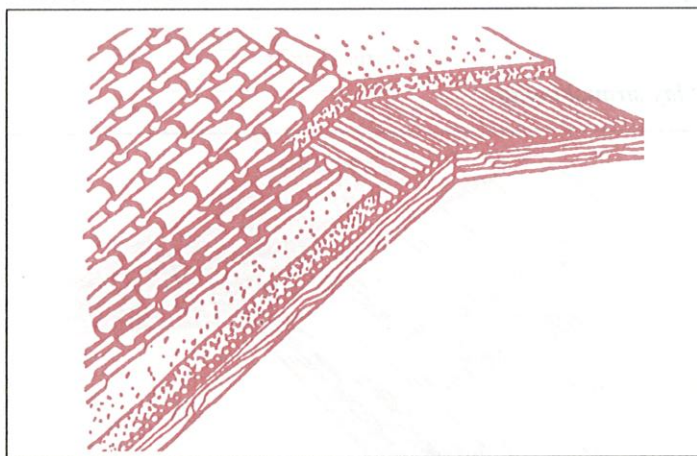
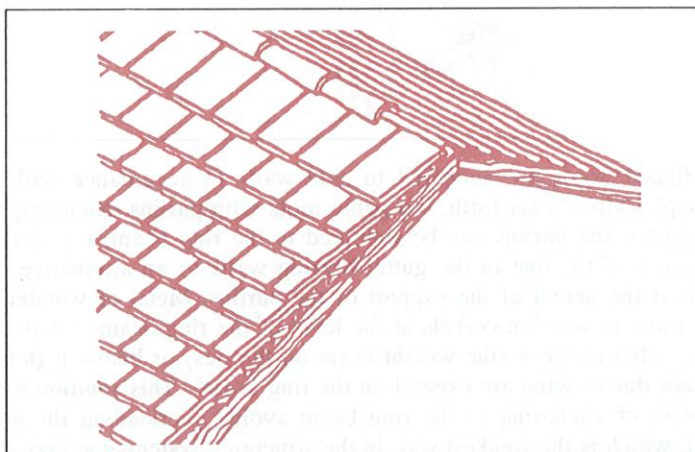
These shingles consist of a layer of straw - visible on the roof - held in two layers of clay of which the second is visible on the underside. The



clay is protected from the rain by the straw which is protected from fire by the clay. The shingles are easy and economic to produce. Their length varies from 90 cm to 1.20 m and their width from 45 cm to 1.5 m, although a width of 60 cm is easier to lay.

The average weight of a 20 cm thick roof in this material is 50 kg per  $\text{m}^2$ .

(b) *Tiles*



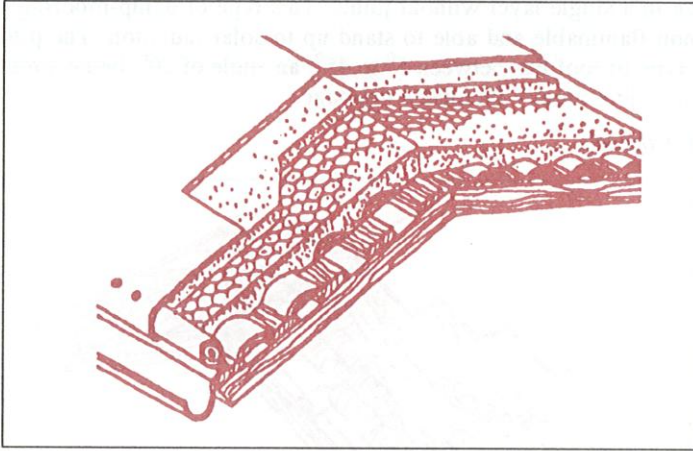
Two types of tiles are used: flat single-lap tiles (e.g., Brazil) and curved tiles (e.g., France) in strongly stabilized clayey earth. These materials freeze easily except when they are overstabilized in which case they are no longer really economical.

Clay tiles made with phenolic resins are still in the experimental stage.

(c) *Roof mortar*

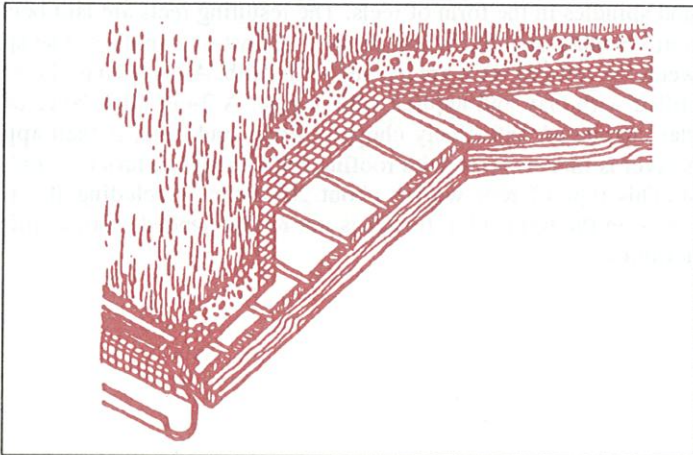
In certain countries (e.g., China) highly clayey soils are used instead of mortar to secure slates or even roofing flags. This waterproof mortar (saturated clay) can also be used to secure curved tiles or Roman tiles (e.g., Burundi).

(d) *Soil layers*



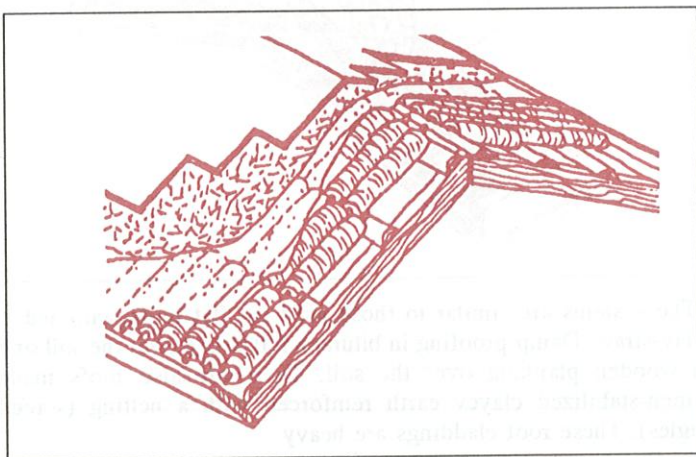
The systems are similar to those used for flat roofs: rammed earth or clay-straw. Damp-proofing in bitumen felt is laid over the soil or over thin wooden planking over the soil. There are also roofs made in bitumen-stabilized clayey earth reinforced with a netting (screed or shingles). These roof claddings are heavy.

(e) *Grass roofs*



Such roofs have several advantages: purification of the air indoors, thermal insulation and buffering, control of indoor comfort by condensation and evaporation, and soundproofing. The thickness of the soil in which the grass grows is at least 20 cm resulting in heavy weight (strong absorption of water), making it necessary to design a special roof frame. In traditional systems, treated wood or flat stones covered with bitumen were used. Nowadays plastic dampproofing is available which is put down in a single layer without joints. This type of damp-proofing must be non-flammable and able to stand up to solar radiation. The pitch of this type of roof lies between  $5^{\circ}$  to  $45^{\circ}$ , an angle of  $20^{\circ}$  being preferred as this pitch greatly facilitates drainage.

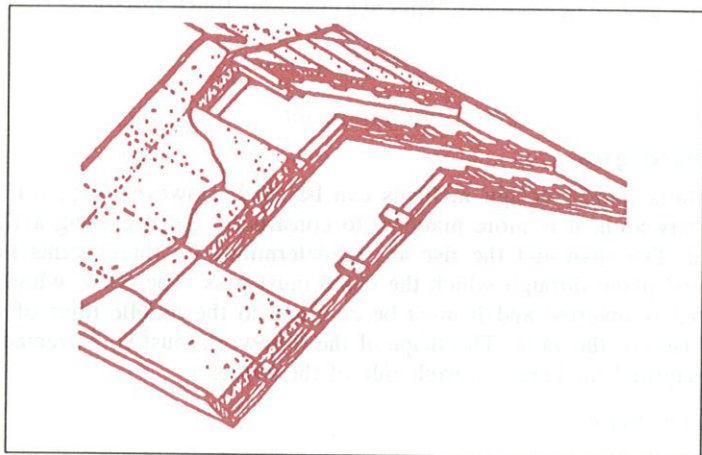
(f) *Earthreels*



These consist of a clayey soil mixed with long fibres and rolled around spindles in the form of reels. The resulting reels are laid between the purlins when still moist and pressed against one another. The spaces between the rows of reels are packed with daub. After drying, the cracks are filled with clay and applied with a mop. A 2-cm thick layer of soil mortar, stabilized with finely chopped fibres and lime, is then applied. This layer is then covered with roofing felt which is in turn covered with sand. This type of roof weighs about  $200 \text{ kg/m}^2$  (including the frame which is on the light side). Its use is not recommended in areas infested by termites.

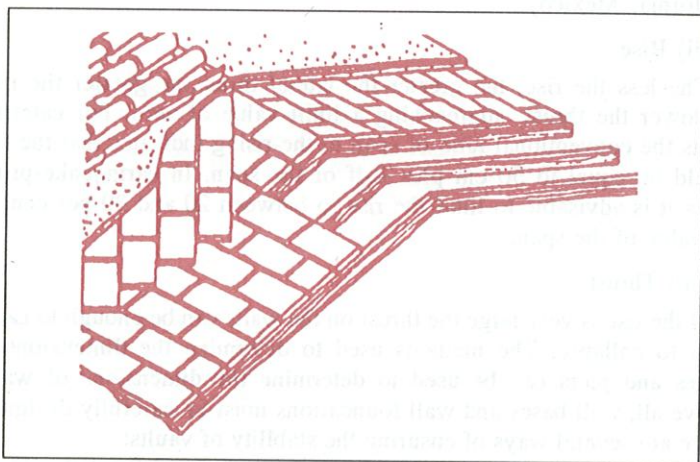


(g) *Panels*



These relatively thin elements are in clay-straw or daub and reinforced with wooden sticks. They are laid directly on simple rafters. They have a low bearing capacity. The panels are held in place on the bottom edge of the roof by a board which takes up the thickness of the finished roof. The ridge pole is covered with a batten and a layer of clay-straw. The roof is given a screed of soil mortar mixed with chopped fibres and stabilized with lime before being covered with bitumen felt.

(h) *Brick roofs*



This uses the principles of the tile floor. It is built in small flat bricks given a rough-cast of plaster. Both the bricks and the workmanship must be of a high standard. The system consists of two layers of bricks, the

first of which is coated by a layer of plaster and the second by a screed in sand and cement mortar. Tiles set in mortar finish the roof.

### *C. Vaults*

#### *1. Basic principles*

##### *(a) Marking out*

Mathematical design methods can be used. However, e.g., for the catenary arch, it is more practical to construct a plot by using a light chain. The span and the rise are predetermined by three points in a vertical plane through which the chain must pass. The curve which is plotted is inverted and it must be confined to the middle third of the thickness of the vault. The shape of the formwork must be corrected to the required thickness on each side of the curve.

##### *(b) Dimensions*

###### *(i) Span*

Vaults with spans of up to 6 m and 15 cm thick have been built in stabilized compressed blocks; whereas spans of vaults in rammed earth rarely exceed 2.5 m. In the Islamic Republic of Iran, the most commonly found span is 4 m. This is the maximum for earthquake-prone regions, and for such regions it has also been established that the ratio of span to length should be equal to 1.5 x width. If the value of span to length is greater than this, there is a danger that the vault will resonate and shatter (according to research conducted by the University of Baja California, Mexico).

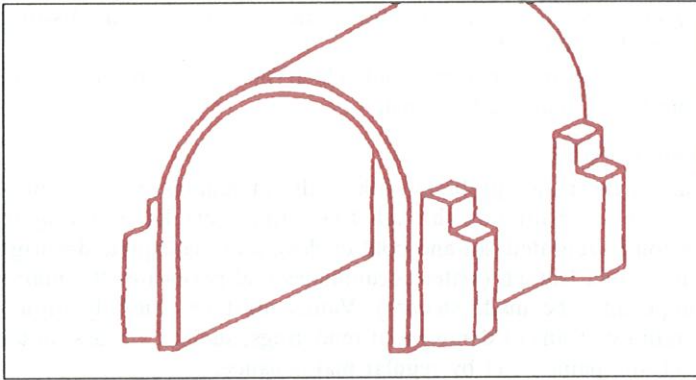
###### *(ii) Rise*

The less the rise, the greater the lateral thrust, the greater the rise, the lower the thrust, approaching a limit value of zero. For catenary vaults the conventional ratio of span to the rising indicates that the rise should be equal to 50 cm plus half of the span. In earthquake-prone zones it is advisable to limit the rise to between 20 and 30 per cent of the value of the span.

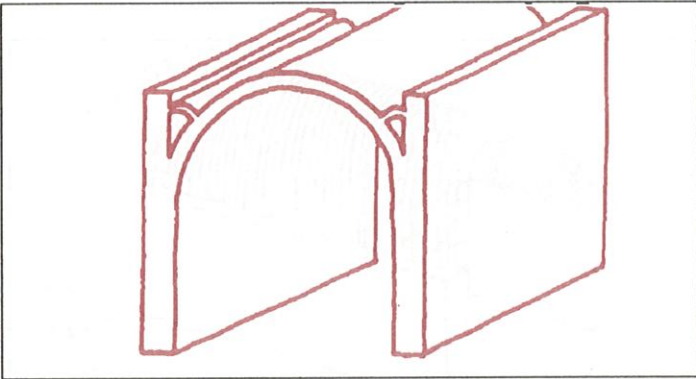
###### *(iii) Thrust*

If the rise is very large the thrust on the walls can be enough to cause them to collapse. The methods used to determine the dimensions of arches and piers can be used to determine the dimensions of walls. Above all, wall bases and wall foundations must be carefully designed. There are several ways of ensuring the stability of vaults:

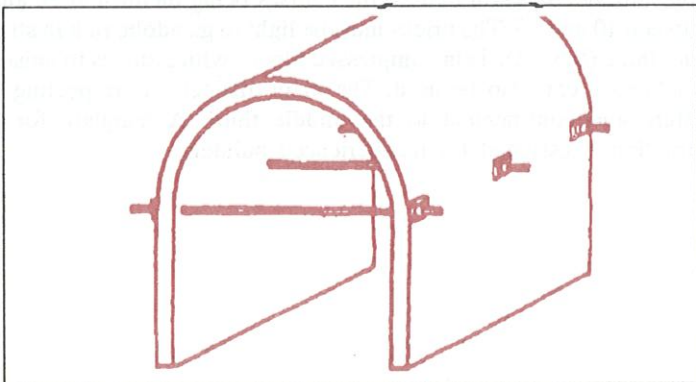
(a) Thick walls: these require a great deal of material and should not be weakened by large openings;



(b) Buttresses which must be supported by good foundations linked to wall foundations;



(c) Prestressing load (parapet or principle), which transforms lateral thrust into vertical thrust;





(d) Tie bars which carry the thrust; these must be evenly distributed and securely anchored;

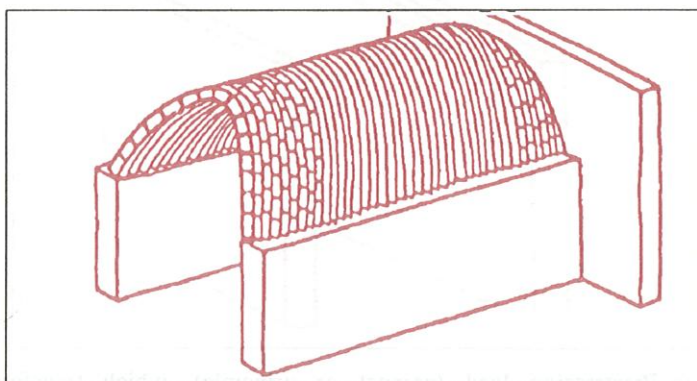
(e) Tying taking up thrust and which should be able to resist the bending forces induced by thrust.

(c) *Waterproofing*

This is the major problem with vaults in regions where rainfall is heavy, due to infiltration through fine surface cracks (resulting from expansion in repeated hot and cold cycles), and inadequate drainage at the crown and haunch (water accumulates and permeates the material: the slope must be made steeper). Vaults must be carefully protected from rain by means of damp-proof renderings, such as washes, bitumen felts, elastic paints, and by regular maintenance.

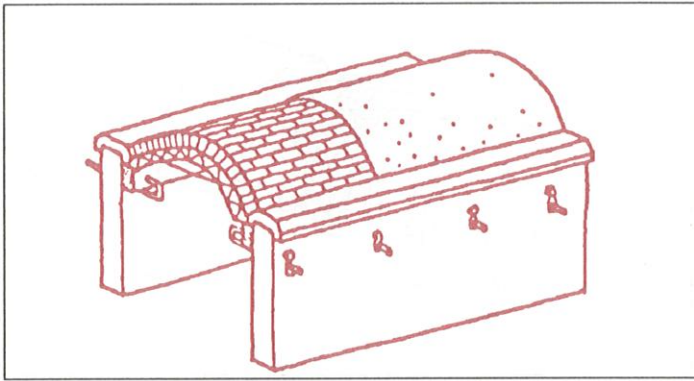
## *2. Design details*

(a) *Bricks - without formwork*



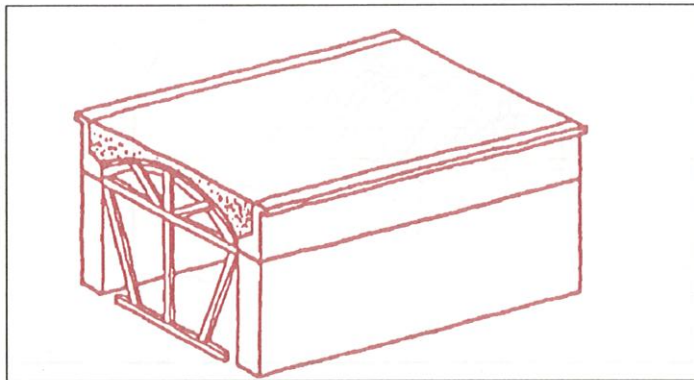
The "Nubian-style" method exploits the mutual friction of the bricks and the adhesion of earth mortar, the courses being inclined at an angle of between 10 and 15. The bricks must be light (e.g., adobe rich in straw) and not thick (5-6 cm). Thin compressed blocks with grooves to enhance their adhesion can also be used. The main difficulty is respecting the curvature and confinement to the middle third. A template for the construction is essential for inexperienced builders.

(b) *Bricks - with formwork*



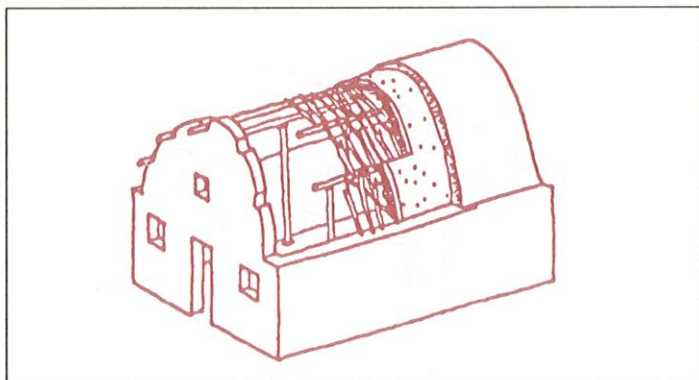
The formwork makes it possible to work parallel to the walls. It can be heavy and fixed or light and sliding. In the latter case, the builder proceeds in successive layers of bonded bricks or even in rings. The setting of the keystone of the arch must be carried out with care.

(c) *Rammed earth on formwork*



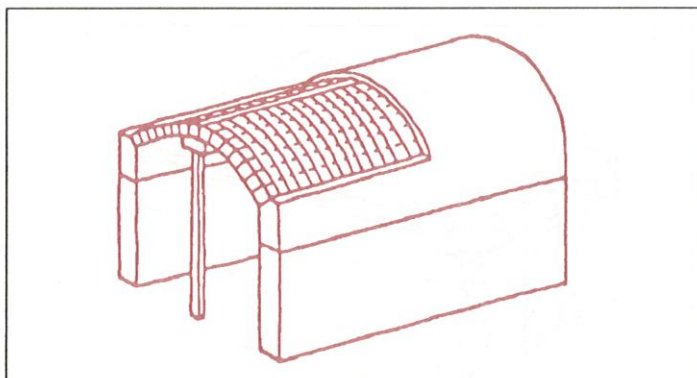
Although rarely used, this construction system does exist. Monolithic arches made of rammed earth and on formwork are generally dropped and held in position by ties. The layer of earth above the extrados is given a gradient. The formwork is very heavy and fixed (ramming stresses) and cannot be used for several days.

(d) *Mud over frame*



An arched structure consisting of interlaced branches is covered with mud to which cow dung has been added. The rigidity and water-resisting qualities of the system are precarious.

(e) *Prefabricated elements*



Hollow elements are prefabricated by double-acting hydraulic presses. The system is highly sophisticated and requires the use of concrete bars to provide the prefabricated vault with a high degree of stability. The vault is assembled in small half vaults assembled on a ring.



## *D. Domes*

### *1. Basic principles*

The dome is a vault of circular cross section the intrados of which is generated by the rotation of an arch about its vertical axis. Like the arch and the vault, the advantage of the dome is that it uses the material in compression.

The best function of the dome is to cover enclosures totally. Like the vault, the dome is not suited to regions with heavy rainfall. Domes perform well in earthquakes; it is the walls that are rather fragile, and which must be well-designed or reinforced by buttresses and tying.

From an architectural point of view, the dome poses certain problems with respect to the design of the enclosed spaces.

Considerable heights are achieved with unflattened domes. The normal diameter of adobe domes is about 4 m (Islamic Republic of Iran), but diameters up to 7 m have been achieved using stabilized compressed blocks.

Another problem connected with domes is their acoustic resonance which renders them unsuitable for certain purposes unless special stretched materials, or sophisticated design, are used.

Simply shaped domes built in isolation are easy to construct, but when a project involves a series of domes, arches and vaults, the site must be well-organized and the building crew experienced.

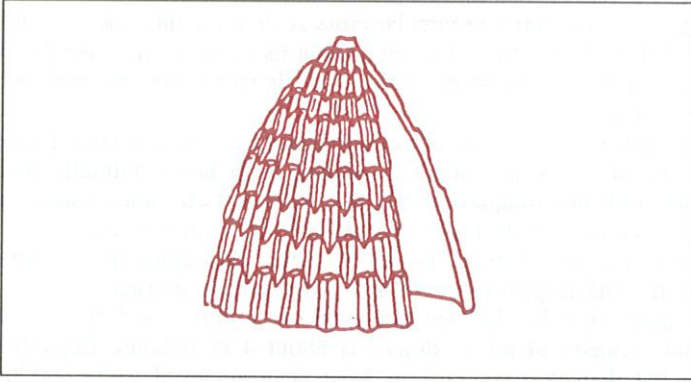
It is also possible to construct two-layer domes where, for example, the extrados is raised and the intrados dropped - thus providing an insulating cushion of air between the two layers and a better gradient for draining off rain water. Openings can also be made in domes without affecting their stability, except in earthquake-prone zones.

Traditionally, domes are waterproofed with a screed, (e.g., bitumen, lime or by surfacing with burnt brick and ceramic tiles (e.g., Islamic Republic of Iran).

The supporting structure can vary greatly depending on the plan. The height of the walls, the diameter of the dome and its centring must be adapted to this. A spherical dome on a circular plan poses no problems, but square, rectangular or pentagonal plans give rise to complex setting out and necessitate the construction of intermediary supports such as squinches and pendentives.

## 2. Design details

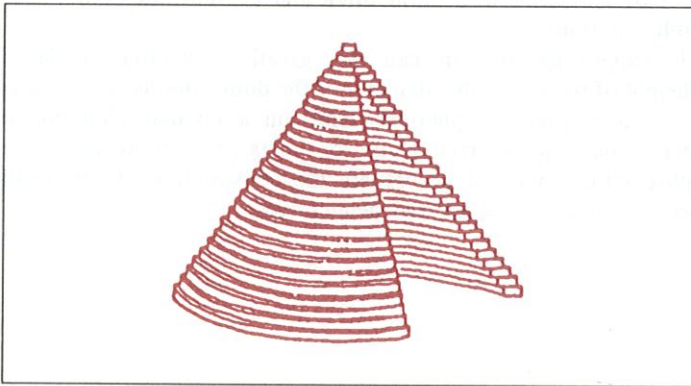
### (a) *Monolithic domes*



These are domes built by hand, using pottery techniques adapted to architecture. A case in point is the famous shell-shaped dwellings of the Mousgoum tribe of Cameroon. Examples of this are becoming increasingly rare. They consist of a highly cohesive specially prepared earth shell, 15 to 20 cm thick at its base, 5 cm thick at the top and 7 to 8 m high. It is constructed without scaffolding, but a surface relief gives footholds while at the same time dividing run-off effectively reducing erosion.

Modern versions using rolls of extruded earth have been tested in Germany, where the construction of a rammed-earth dome has also been tried with success.

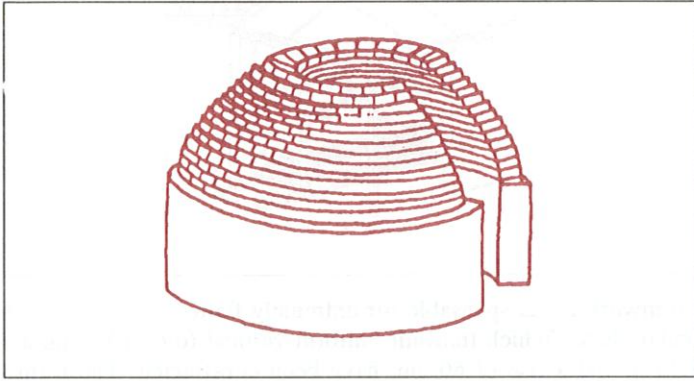
### (b) *Corbelled domes*



These are erected by building inwards on successive horizontal courses, which hold together due to the adhesion and cohesion of the matter. This principle has been adapted to conical and pyramidal

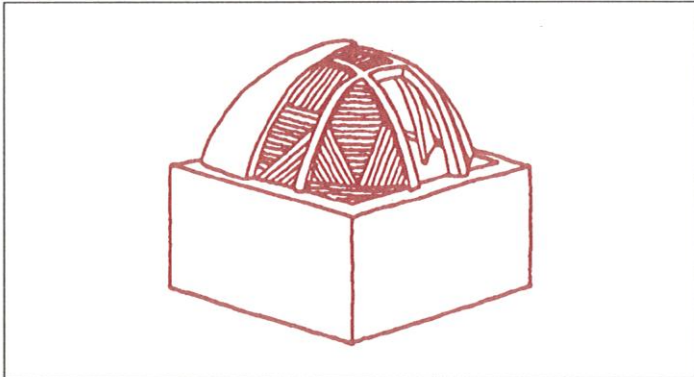
shapes (projects in Honduras in the 1980s), but the execution is very slow since it is necessary to stop for drying every two or three courses of bricks.

(c) *Domes with inclined courses*



This involves the construction principle developed by traditional Nubian architecture (Upper Egypt) and adopted in designs by Hassan Fathy (village of New Gournia project). The construction system is very cunning and rapid.

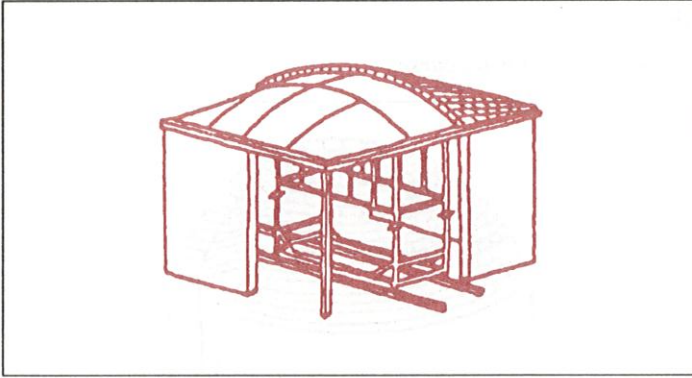
(d) *Domes on sacrifice formwork*



This method is typical for the architecture of Niger and Nigeria, among others. The dome is built using brushwood and small branches and then covered with earth, which makes the structure rigid and waterproof. Inside the wood ribs are also covered with earth.



(f) *Domes on formwork*



Formwork is indispensable for extremely flattened domes. In India, funicular shells (which transmit uniform vertical forces) having a span of 5.20 m and a rise of 60 cm, have been constructed. The formwork must be light, mobile, and easily dismantled to be effective.

## VII. FIREPLACES AND SERVICES

### *A. Fireplaces*

Earth can be used in an immense variety of applications, including the construction of kilns and furnaces, fireplaces and flues. Such equipment functions well but requires regular upkeep, without which it is liable to deteriorate rapidly. Burnt earth materials are better suited to building such items and are clearly more durable. The use of earth as a monolithic material, e.g., rammed earth or cob, is acceptable, but is not recommended for making fireplaces or flues, because of cracking and shrinkage problems. Stabilized compressed bricks or very compact adobes are serviceable.

There are two possibilities for using earth to build fireplace: either the hearth and fireplace surrounding it are constructed using sun-dried earth, or the fireplace is constructed using burnt materials and the hearth built in raw earth. If the earth is very clayey, the firing of the fireplace flue will cause shrinkage cracking which must be plugged with the greatest of care. If the earth is less clayey, the heat will cause drying and the material will lose its cohesion and become friable. These are the problems associated with burning at low temperature; a temperature ranging from  $600^{\circ}$  to  $900^{\circ}\text{C}$  is necessary to produce a quality burnt material.

While it is true that the inner facing of kilns can be made in raw earth as opposed to the outer facing for which burnt material is necessary, it is also true that firebacks must be made of refractory material. Internal cracking in a kiln is acceptable; it is less so in the case of an indoor chimney. The mortar used can be made from unstabilized earth to which ground burned brick has been added, the latter serving as sand. All of the cracks in the hearth must be plugged with care. Flues in unburnt earth are not recommended. Earthenware incorporated into the thickness of the walls or built outside, i.e. external flues, is preferable. This precaution guarantees the stability of the flue and helps to prevent noxious gases from escaping through the cracks. Inside, ducts can be rendered in raw earth but chimney pots on the roof should be in burnt brick.

No fire can be kindled until the masonry of the oven or fireplace has completely dried. The first fire should be moderate and slow-burning; an intense fire is liable to damage the structure. Cooling should also proceed slowly. With the second firing, the temperature should be raised slightly so as to bring about controlled smoking, e.g., with wet leaves, at the end of burning when the fireplace is hot and has expanded. In this way any possible escape of smoke can be detected through cracks which must then be plugged. Where earth and metal meets, e.g., at the cover of the oven, a little salt can be applied, since heated salt hermetically seals cracks.

## *B. Services*

### *1. Plumbing*

The installation of supply and drain pipes in earth homes must be carried out with special care, as constant moisture can have very serious consequences. In principle, every attempt should be made to centralize the plumbing to the greatest possible extent so that it can be easily examined and maintained, while avoiding the risk of defects which would be difficult to locate.

All waste water must be carried outside the house well away from the foundations. Gutters and service access holes must be carefully maintained.

Inside the house, attention must be paid to the fittings in rooms containing plumbing installations (kitchen, water closets, and bathrooms) as there is a considerable likelihood of damp. They must be ventilated and provided with easily accessible floor drains. Floors must be adequately sloped for drainage. Showerbaths must stand away from earth walls and these must be protected by a ventilated waterproof coating (danger of condensation).

Attention must be paid to ducts that may cause condensation, e.g., those for air conditioning and heating. It must be possible to drain any such condensate water away. The slope of ducts and drip channels must be adequate or else the ducts must be insulated.

The incorporation of pipe and ducts into earth walls is not advisable. The best course is to make use of some part of the structure which is to make use of earth (stone or concrete base courses, vertical and horizontal tying, wooden frames) for securing them. Such fastenings must be carefully constructed to prevent leaks.

The anchoring points of pipes, ducts and appliances must be planned in advance. Wooden blocks of a good size firmly anchored in the walls will allow the fastening of brackets, hoods and rings. Wash basins, sinks, water-heaters expansion tanks etc. can be fixed on, for example, ventilated wooden structures. Walls must be protected against any possibility of splashing by using protective facing and plinths.

### *2. Electricity*

An earth house, like any other house, is supplied with electric power by means of a connection with the existing mains.

If the mains supply is underground, connection poses no problem and can be effected at terminals and in cabinets (external meters). In the case of large housing complexes the connection of the electrical networks to the houses must be worked out in advance.

When the mains supply is from overhead wires, the problem of the connection of the mains supply to the house requires careful attention. The wires are very heavy, and once they are taut, induce tensile stress



and vibrations. Consequently, the anchoring of mains supply brackets directly to the earth walls themselves is not recommended. They should rather be anchored to parts of the house that can resist tensile stress, e.g., vertical and horizontal ties.

It is advisable to incorporate sheathed wiring as well as all shielded conductors into the thickness of the floor screeds (widespread practice) or into "hard" base courses where recesses or anchoring points will have been provided. Maximum use must be made of materials other than earth for fastenings: e.g., the wooden framework in clay-straw structures. Generally speaking, grooves should not be made in earth walls for wiring but this is a viable solution if a rendering is provided. In that case, the grooves are plugged with earth or mortar and finished with rendering on netting. It is wise to make use of plinths and doorframes or to provide a cable duct on the ring beam or in the thickness of floors.

Switches and sockets can be flushfitted or surface mounted. If they are flush-fitted they must be very deeply embedded; a properly designed fitting must be used for this purpose. The bedding can be in plaster. Surface-mounted fittings should preferably be installed on the base course, on plinths, on the subframes of openings, and vertical wooden frames. When mounting fittings on earth walls, small wooden blocks integrated in advance in the walls and embedded in deep plaster should be provided for mounting purposes.

## PART THREE

# SURFACE PROTECTION

### I. BASIC CONSIDERATIONS

The very large majority of the world's dwellings constructed in earth and built, for the most part, in rural environments, all suffer from the same defects when exposed to bad weather: surface erosion, partial crumbling, unhealthy conditions because of constant humidity, walls hollowed at their base etc. It is thus extremely desirable to propose effective solutions for their restoration and protection. These solutions can, moreover, be applied to buildings which are still sound but which are liable to deteriorate if not effectively protected. Furthermore, it would be best if these solutions were integrated into current or future construction in earth so that these typical defects could be banished forever.

Apart from this, a coherent and truly feasible revival of construction in earth can hardly be envisaged if the material does not satisfy requirements as well as other modern materials do. This objective will be attained by the material itself and the construction techniques involved as well as by using a wide range of techniques which can bring about a marked reduction in the sensitivity to water of buildings constructed in earth.

Like surfaces of many modern buildings, earth surfaces must be capable of being given protective coatings which meet current specifications for wall facings. Earth will only enjoy a quality image when it is regarded as a truly modern material. The necessity of protecting the earth used in the structure, long before being approached at the level of surface protection, remains subordinate to the quality of the material, design, and the construction procedures used for the structure. Between the stabilization of the material and the systematic employment of non-eroding rendering - the two most common approaches adopted - the range of solutions for the protection of surfaces is sufficiently wide to ensure durability, without having to resort to "miracle cures". However, of the numerous structures examined, stabilization and rendering only rarely appear to be satisfactory, and do not always provide a lasting solution.

#### *A. The need to protect*

Every wall built of earth should be able to stand up to the effects of damp and the direct action of water. The ability of an earth wall to withstand water is above all dependent on the quality of the soil itself, its grain-size distribution, structure, density and porosity. It can be improved by adding a stabilizer under controlled conditions, or protected with protective coatings compatible with the material, or by

taking protective measures in the design and construction stages, such as broad eaves, porches, and so on. The protection offered by renderings can take many forms, and varies considerably from region to region as regional conditions impose specific protection requirements on the material.

Generally speaking, in temperate regions, when the soil is of a satisfactory quality, earth walls stand up to weather erosion insofar as they are built on good foundations or footings and are protected at the top. If the soil is of moderate quality, stabilization can bring some improvement without, of course, neglecting the basic protective measures at the top and the bottom of the wall. In dry climates, earth walls protected at the top by an edge of the roof, or some other "hat", stand up well to water, if they are not liable to flood damage. In any region where rainfall is low, or medium, protection against rain can be afforded simply by taking architectural precautions. In contrast, in regions with high rainfall and driving rains with a virtually level trajectory (e.g., in the tropics), protective coatings are indispensable. This precaution is essential in regions where climatic vicissitudes go hand in hand with an architectural tradition which provides no protection either at the top or the bottom of the wall (e.g., mud architecture in the Sahel). Similarly, coatings may be more or less necessary depending on the construction technique.

Thus, for monolithic soil walls (e.g., cob, rammed earth, clay-straw) which are suitably protected and uncracked, the need for protection is less than for walls in earth masonry (e.g., adobe, compressed blocks) where the water may penetrate at the brick mortar interface, i.e., the joints.

In principle, protective coating is not necessary for well-built structures in stabilized soil. Stabilized-earth walls stand up well to bad weather for many years. Good base courses are, however, not pointless. It can be expected that a soil wall which is unprotected at the top will start to undergo local deterioration. The protective covering may thus be useful when the need becomes apparent, several years after construction. Even so, the decision to protect the surface may be influenced by specific conditions relating to the use of the rooms and subsequent maintenance.

When it is decided to use a coating, an effort must be made to obtain the smoothest and finest outer surface possible. For example, with rammed earth, stones will normally be placed in the centre of the wall and the outer surfaces rammed slightly more. When it comes to providing a surface dressing, the stones will be concentrated on the outside edge of the wall and the wall may be less rammed in order to obtain a slightly open structure. After a first season of exposure to the elements, the stones will be exposed and will facilitate the adhesion of the rendering. In this case, the middle and the inside surface of the wall will be strongly rammed in order to provide the necessary strength.



Prior to deciding on the use of surface protection, three alternative solutions should be considered:

(a) Building a well-designed structure with an anti-capillary barrier, overhanging roofs, gutters and downpipes, with good drainage and protected against the wind, and constructed according to the rules and sound technical specifications.

(b) Stabilization, avoiding, if possible, stabilizing all the material (excessive cost) and limiting the stabilization to the outer surface of the walls; or by stabilizing the waterproof coating (wash, or distemper), rather than the whole thickness of the wall;

(c) Application of a coating several years after the wall has become less smooth, giving good appearance. The deterioration of the surface of a wall in earth is in fact very rapid in the first two years but stabilizes itself quickly afterwards.

It is above all advisable to protect structures against wind as this, associated with rain, can be particularly corrosive, even with very brief and short squalls. Finally a coating which is not suited to the earth, or which is ineffective because it has been poorly executed, can be more harmful than if it had not been applied at all.

### *B. Functions and requirements*

The main functions of a protective coating are the protection of the wall against bad weather and impact, the extension of the service life of the walls, the improvement of their appearance by hiding imperfections in the rough work, and giving walls an attractive colour - without, however, masking defects - and improving thermal comfort.

These functions should not allow the cost of the coating to get out of hand. The functions may result in contradictory requirements. For example a good coating should be impermeable to rain outside the structure but remain permeable to moisture from the inside. Renderings are very susceptible to climatic stresses (variations in temperature, sun, rain, and frost) and may deteriorate. However, they must not lead to the irreversible deterioration of the support (e.g., loss of wall material stuck to pieces of rendering).

A good protective coating should adhere well to the support without provoking the loss of wall material, be flexible in order to allow for the deformation of the support without cracking, be impermeable to rain, be permeable to water vapour in the wall itself, be frostproof, and, finally, have a colour and texture compatible with the local environment.

### *C. Deficiencies in earth walls*

The numerous symptoms of the deterioration of soil walls are related to the influence of local climatic conditions, such as rain, frost, and great heat, as well as lack of maintenance, lack of knowledge about how to improve deteriorating.

Observations of renderings indicate that: either the renderings are in good condition - they can be old and well-maintained, or new (less than five years old) and recently applied - or they are in poor condition - they may be very old, 50 years or more, and their durability praiseworthy, compared with modern renderings. These are usually renderings based on non-hydraulic lime. New renderings in a poor state are often in a very bad way after no more than five years, the shortest period possible in which a rendering can be evaluated. These are often cement renderings. Cement displaces the accumulated know-how acquired with older renderings, so that although it may have remedied certain problems (e.g., speed of application, reliability), it does not really provide a lasting alternative. The loss of traditional know-how and the absence of modern know-how is, thus, often a major cause of deficiencies.

The same applies to the maintenance of dwellings. Formerly, renderings were considered more as wearing layers which had to be regularly maintained (e.g., refreshment of washes). Now it seems that home maintenance is slowly disappearing as a social custom in the majority of rich countries. The shift is due to the excessive confidence in certain products (e.g., cement, paints).

In many developing countries, maintenance of structures continues to be a significant social link in the community. The festive regular renewal of the rendering of mosques in Mali, with the whole village taking part, is a typical example.

### *1. Deficiencies and their causes*

Conventional symptoms may range from a simple dirty streak (marrying the appearance of the structure) to a change in composition. The main deficiencies are poor composition, a lack of flexibility or poor adhesion to the support, and poor waterproofing. The reasons for these defects include the use of unsuitable materials, careless application, structural tension, a lack of maintenance and a defect in the supporting structure, such as subsidence, and cracking.

### *2. Symptoms*

Defective renderings on soil walls are revealed by the fairly typical symptoms discussed below.

#### *(a) Crumbling*

The rendering can be easily scratched with a fingernail and disintegrates. It is mainly seen in accessible places such as the reveals of doors and windows.

#### *(b) Erosion*

Eroded renderings are thin and no longer protect the wall. The erosion may be even and the increasingly thin rendering tends to

disappear. Erosion may also be localized and the rendering may be left as isolated patches.

(c) *Crazing*

The surface of the rendering deteriorates into an infinity of thread-like cracks, permitting the access of water.

(d) *Cracks*

These may be few in number but gape or be very numerous and more or less closed. Fine cracks or crazing may develop into larger cracks. There is a danger of penetration by water and frost.

(e) *Blistering*

This may be localized or be overall swelling of the rendering, and is visible as a bump or series of bumps. The surface of the wall sounds hollow because the rendering is no longer attached to the wall. There is a danger that pieces of rendering may fall off the wall.

(f) *Blowing*

The rendering is pitted with small craters with a diameter of no more than 20 mm and of variable depth. Blowing occurs quite often on lime-based renderings. There is a danger of water penetration and frost damage.

(g) *Efflorescence*

The rendering is discoloured by small white or grey rings. These are crystalline or amorphous deposits of an alkaline or alkaline-earth character and include sulphates, carbonates and nitrates. These accretions of salt may bring about the disintegration and loosening of the renderings.

(h) *Infiltration*

Water is trapped in the thickness of the rendering resulting in the appearance of efflorescence or in triggering off cracking and loss of adhesion. Once this has started the rendering may disintegrate very rapidly.

(i) *Dark patches*

These may appear in the form of black or brown patches. They are the result of the decay of organic matter left after water has dried up or by a localized flow of water.

### 3. Mechanisms

(a) *Expansion*

Frost or alternating wetting and drying can cause clay fraction to expand at the wall/rendering interface. If the rendering is too rigid, it will first crack and then crumble. Similarly, on a heterogeneous wall



(e.g., large stones isolated in rammed earth) differences in the thermal expansion of the soil and the stone can cause localized failure.

#### (b) *Shrinkage*

When a rendering first dries it shrinks, putting the material under stress. There may be loss of adhesion and loosening. This happens when a rendering is too rigid and the support is too smooth. When the support is rough, the same rendering can cause cracking. The cracks may be clearly visible and few in number when the adhesion is low, or numerous and fine when adhesion is high. The thicker and stronger the rendering, the wider will be the cracks. They appear on the outer face of the rendering if the contraction is the result of exposure to wind or sun.

Cracks may also develop at the interface and advance towards the outer surface on dry walls which contain little water, resulting in capillary suction operating from the rendering/support interface. The most sensitive spots are recessed corners and the angles around bays.

#### (c) *Vapour pressure*

Water vapour may accumulate in the form of condensation at the rendering/support interface. Blistering may be observed, heralding detachment. This phenomenon is typical for maritime and temperate climates where internal vapour pressure is higher than external vapour pressure. This differential pressure causes the vapour to migrate through the wall and the rendering. These must be permeable; waterproof or excessively thick renderings should be avoided. The opposite problem - internal condensation - may arise in tropical climates or in air-conditioned rooms.

#### (d) *Others*

Other mechanisms are the infiltration of rainwater or drips entering via cracks (accumulation of damp), the use of unsuitable materials (poorly slaked lime, old cement), efflorescence caused by moisture or excessive smoothing of the rendering (appearance of laitance on the surface), attack by micro-organisms (lichens, algae, mosses), and plants (creepers, ivy), sloppy application (poor preparation of the mortar or support), frost or very hot conditions, rain erosion, wind erosion, and damage due to mechanical impact.

### *D. Good practice*

The main defects which can be observed in renderings are due to:

- (a) Incorrect composition of renderings and defective constitution;
- (b) Hasty application, and a failure to respect the fundamental rules of the art;
- (c) Poor site conditions;
- (d) Incorrect or sloppy application.

Taking heed of good practice, know-how, and the literature is absolutely essential. Moreover, the application of lasting renderings to

earth walls demands special care and attention, the most essential support, and the use of binders which are not too strong and which result in fat and plastic mortars.

### *1. Constitution of renderings*

Single-coat renderings should be avoided, as they are too thick and too dense. Renderings based on mineral binders (lime, cement, and clay soils) should be applied in several coats, at least two - with an uncracked second coat - and preferably three, with a render, float, and set. This application in three coats is particularly important for conventional lime-based and cement-based renderings, the thickness of which diminishes with the float and the finishing coat.

#### *(a) Render*

This is the first coat applied to the support and provides the support for the float. It is made of a fairly fluid mortar, generously provided with binder, and very finely ground. It is energetically applied with a trowel and to a well-prepared support. Its thickness ranges from 2 to 4 mm and the surface has a rough appearance.

#### *(b) Floating coat*

This is an intermediate coat which takes up any unevenness in the support. It gives the rendering its solidity and impermeability while staying permeable to migrations of water vapour. The floating coat is applied two to eight days after the render, in one or two layers, and has a final thickness of between 8 and 20 mm. The floating coat will have no cracks and is level to the float. Application in several layers (if possible) makes it possible to plug fine cracks in the underlying coats. The amount of binder used is less and finer sand is used. The floating coat is grooved with the trowel or with a brush to improve the adhesion of the finishing coat. The curing of the floating coat must be perfect.

#### *(c) Finishing coat*

This coat finishes the protective rendering and plugs any cracks in the floating coat. It is the decorative coat, both with respect to colour and texture. The finishing coat has the lowest binder content, as no cracks at all can be tolerated. Care should be taken that the finishing coat is not compressed too much with the float, because of the danger of causing the moisture to come to the surface and of crazing. This is the coat which may have to be redone from time to time.

### *2. When to apply*

An earth wall should never be rendered before:

- (a) Shrinkage has stabilized; this may take several weeks or several months. Times may be six to nine months for thick rammed earth, three

or four months to a year for monolithic walls in cob or clay-straw; and within a year and for building with adobe or compressed block walls;

(b) Any settlement in the wall has taken place; the carcassing must therefore be complete, including any loads due to floorboards and the roof;

(c) Migration of water and moisture vapour due to drying has stopped. The internal core of the wall should not contain more than 5 per cent water by weight, and this can be a guide to when to start rendering works. Weather conditions when the work is in progress play an essential role.

### *3. Conditions of application*

Rendering should not be done in excessively cold weather nor when it is very hot. Work should be avoided in driving rain as well as in sun and violent wind, and when it is very dry. The best climatic conditions are when it is moderately warm and slightly humid.

Horizontal and vertical joints should be made with a view to completing panels of 10 to 20 m<sup>2</sup> in size in one go. Walls should be finished on the same day as they are started.

Particular care should be paid to intersections, and reveals in bays. Where the support changes (e.g., earth and wood), the rendering should incorporate reinforcement at that point. The rendering should not continue to ground level (capillary action), but rather a joint should be made at the level of the floating.

Excessively rapid drying of the rendering should be avoided by spraying water on the surface (morning or evening), and by hanging up protective sheets against heat and rain action which could wash off the rendering. The environment has to be kept humid.

The ingredients (binders and sands) must be of good quality and mixing must be properly carried out.

In warm climates, it is advisable to apply a wash to the rendering about three weeks after application, in order to plug any cracks.

### *4. Application techniques*

Application should be done by hand, for earth-based renderings. Balls of mortar are thrown energetically against the wall and then smoothed with the palm of the hand, avoiding excessive finger pressure.

When using conventional tools, such as trowels or floats, excessive compression should be avoided.

Use should be made of a brush or broom for a liquid render coat, with an adjustable hand-operated plaster blowing machine to give a Tyrolean finish.

With a pneumatic blowing machine or rendering pump, make sure that the blowing pressure can be regulated so as to be neither too strong nor too weak.



### *5. Preparation of the support*

This preparatory phase in applying the rendering must be carried out with particular care.

#### *(a) Dust removal*

The support must be free of all loose and crumbling material, and dust. It must be carefully rubbed down and brushed with a metallic brush.

#### *(b) Moistening*

The support must not absorb the water contained in the rendering, as this may hinder setting and reduce the adhesion of the rendering. The support must, therefore, be moistened in order to avoid capillary suction, but not too much, as a film of moisture could be created which reduces adhesion. The support should be sprinkled until the wetting agent flows off. This operation may require several applications of water.

A distinction is made between supports stabilized through-and-through or only on their surface (moisten until rejection), and unstabilized supports, which should hardly be moistened at all (risk of causing the clay to swell). On non-stabilized supports, an impregnating wash can help provide a rough surface to create support for the rendering.

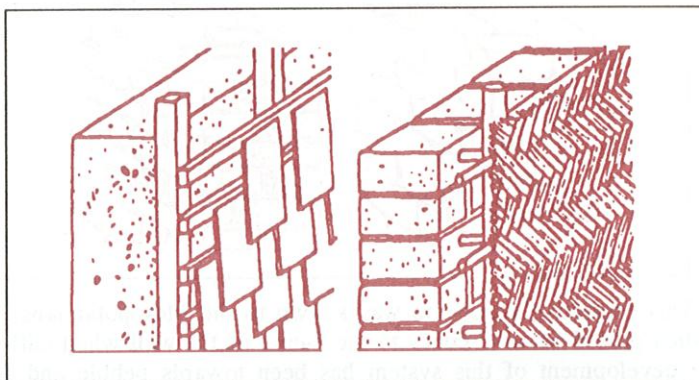
#### *(c) Anchoring points*

On brickwork the joints must be roughened with a jointer. With rammed earth, brushing reveals the stones. Good anchoring points ensure good adhesion of the rendering.

## II. SURFACE PROTECTION

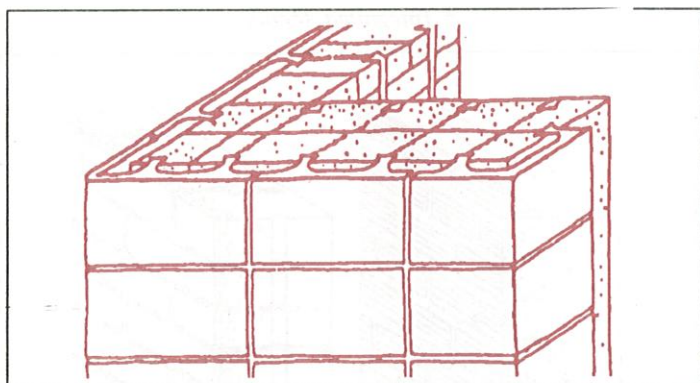
### A. Types of surface protection

#### 1. Weather boards



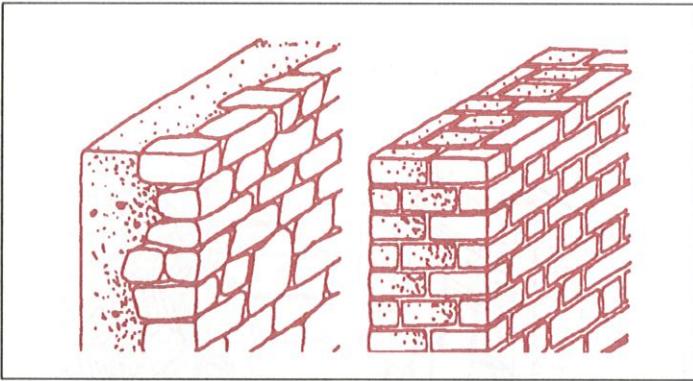
These are coverings attached to the wall and fixed to a secondary structure in wood or metal. Weather boards may be in any of a variety of materials, such as slabs of wood, planks, boards, tiles, cement-fibre elements, corrugated iron, external insulating systems, and so on.

#### 2. Cladding



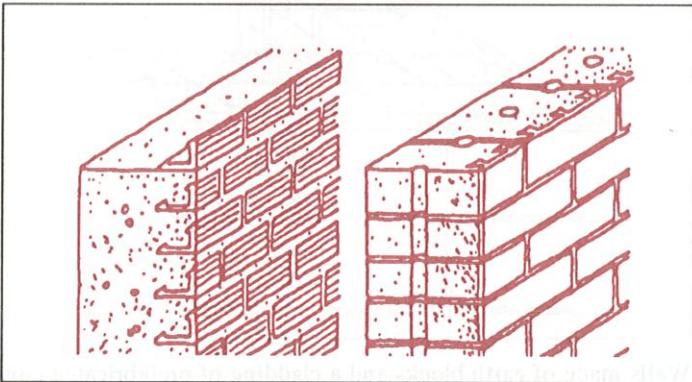
Walls made of earth blocks and a cladding of prefabricated concrete elements were used in Germany in the 1920s. Both the earth and concrete products must be extremely well produced as design tolerances are very limited.

### *3. Facing*



This protective procedure was known to the Mesopotamians, who applied glazed ceramic cones to the facing of the wall when still wet. The development of this system has been towards pebble and burnt brick facings, common in the Asian and Pacific region. The facing is either applied while the rammed-earth wall is still in the shuttering, or applied subsequently. The system may result in a mixed wall, the strength of which is not always uniform, and which may result in unequal subsidence of the wall and revetment-facing. The system is not suitable for use in earthquake areas.

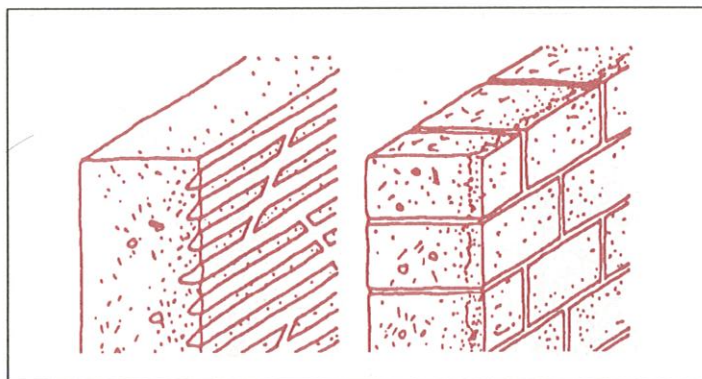
### *4. Integrated facing*



Burnt clay elements which are either flat or "L" shaped are fitted as facing on the rammed earth wall during construction or are included in the earth block during moulding. In the latter case, the adhesion of the facing to the earth block is ensured by dovetail fittings.

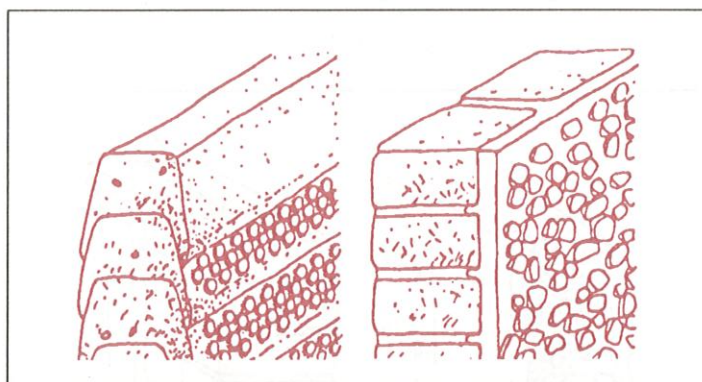


### 5. Twin layers



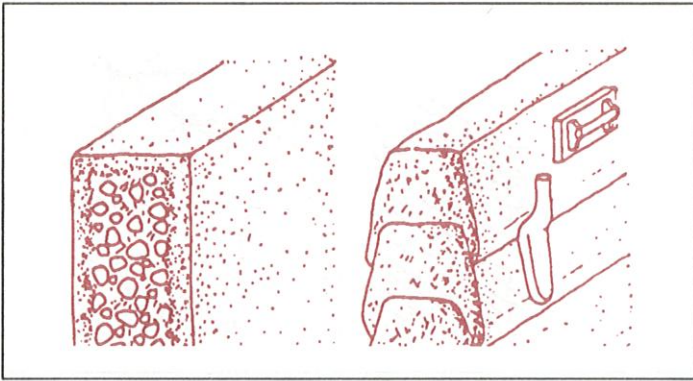
This is a surface stabilization system. With rammed earth this can take the form of the stabilization of the entire outer surface, while still in the formwork, or partial stabilization with layers of mortar or lime. The twin-layer system has also been developed for soil blocks (Burundi, 1952, and EIER at Ouagadougou). It gives excellent results but is slow in production. The effect of the surface stabilization is limited to a thickness of 2 to 3 cm.

### 6. Inlay



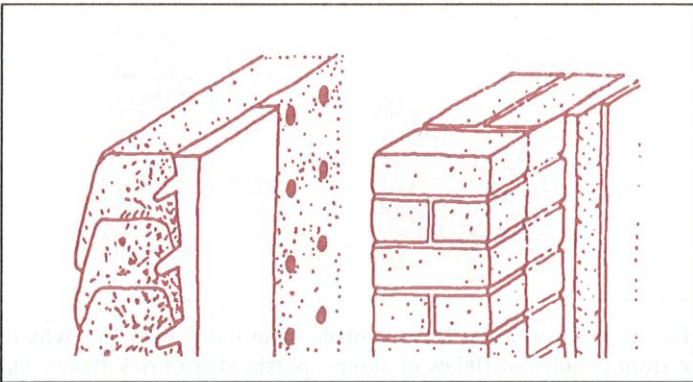
Here an outer wearing layer is made from inlaid elements which can range from pebbles or flakes of stones, potsherds or brick flakes, shells, bottle tops (seen in Mexico), bottoms of bottles and box tops (seen in Khartoum). The work is demanding and requires a large supply of the elements used. Only the most exposed walls are inlaid.

## 7. Surface treatment



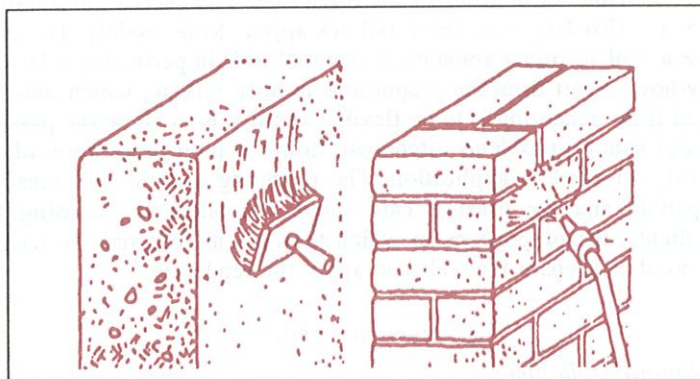
The exposed surface is carefully treated. French builders in rammed earth (*pisé de terre*) finish the wall with *fleur de pisé*. This involves the careful ramming of the outer surface with an extremely fine soil. The surface treatment may also be the finishing of the wall with a wooden paddle, as practised in Morocco. Such external tamping is also carried out in Yemen on cob structures. The surface of the wall can also be rubbed down with a stone for example. Such treatments reduce the porosity of the soil and are effective but should not be carried out when it is intended to apply a rendering.

## 8. Renderings



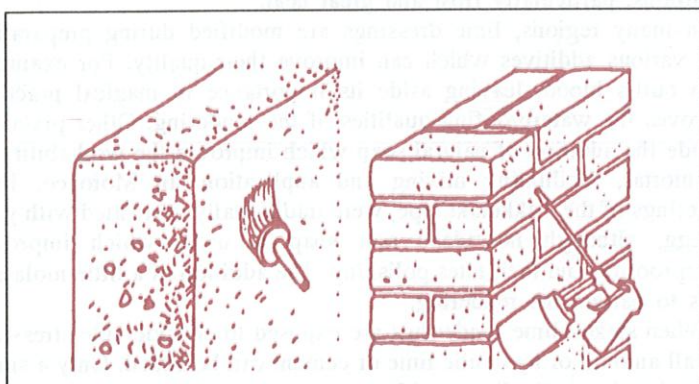
These may be in earth, stabilized earth, or a sand-based mortar to which a hydraulic binder has been added: cement or lime, or some other additive such as bitumen or resin, among others. Renderings can be applied in a single thick or thin layer, or in several layers. Multi-layer renderings perform extremely well but take longer to apply.

## 9. Paint



The coatings mentioned under this heading include conventional paints, and distempers and washes. The latter are cement or lime slurries applied with a brush on walls properly prepared and hydrated in advance. It may also be bitumen applied in the form of a liquid cut-back. A spray-gun may be used to apply them.

## 10. Impregnation



The soil is impregnated with a natural (e.g., linseed oil) or chemical (e.g., silicon) product which confers certain qualities on the wall: impermeability, fixing of fine grains and powders, hardening of the exposed wall surface, colouring and so forth. The impregnating product is applied with either a brush or a spray.

## B. Renderings

The conventional renderings, based on hydraulic binders such as cement and/or lime, and plaster, with or without additives, are well-known. When employed for the protection of earth buildings, this type



of dressing often gives adequate results, but numerous precautions must be taken. While these materials are often used with success, disappointments are also frequent. These failures appear to be mainly the result of the use of incorrect amounts of material and, in particular, a lack of know-how. Apart from the proportions used in mixing, which must be correct if the rendering is to be flexible and if it is to allow the passage of water vapour, problems often arise from the poor preparation of the support and careless application. The rendering and the soil must be compatible and the greatest care should be taken in choosing the ingredients, the proportions in which they are mixed, and the techniques used to prepare the wall and apply the rendering.

### 1. *Alternative plasters*

#### (a) *Non-hydraulic lime*

The best results are obtained with hydrated slaked limes, in the form of extremely fine-ground powder or a paste prepared beforehand. The use of slaked lime as a surface rendering for soil structures is old and well-established in many countries. The hardening of a rendering based on slaked lime is the result of slow carbonation by carbon dioxide in the air, and as a result the dressing should not be too sheltered. The long hardening process makes these renderings sensitive to atmospheric conditions, particularly frost and great heat.

In many regions, lime dressings are modified during preparation with various additives which can improve their quality. For example, fresh bull's blood, leaving aside its importance in magical practice, improves the waterproofing qualities of the rendering. Other practices include the addition of natural soap which improves the workability of the mortar, facilitating mixing and application. In Morocco, lime renderings of the Takkelakt type, were traditionally lubricated with yolk of egg, although nowadays soft soap is used, which improves waterproofing and facilitates polishing. The addition of a little molasses helps to harden the rendering.

When slaked-lime renderings are exposed to considerable stressing, a small amount of hydraulic lime or cement can be added. Only a small proportion is required to avoid excessive hardening or reducing permeability.

Experimentation has made it possible to specify proportions for lime- or sand-based multi-layer renderings and mixed renderings based on lime, cement and sand.

	Lime	Cement	Sand
1st layer	1		1-2
2nd layer	1	2	3-5
3rd layer	1	3	4-5
or			
1st layer	2	1	3-4
2nd layer	2	1	6
3rd layer	2	1	8

(b) *Hydraulic lime*

A distinction is made between natural hydraulic limes and artificial hydraulic limes. The natural limes have the qualities of lime and they harden rapidly with water and slowly in air. This advantage reduces the sensitivity of the new rendering to damp and frost. The artificial hydraulic limes have properties similar to cement and their use should be avoided. In small proportions they can be useful, e.g., 1 part lime to 5 or 10 parts sand.

(c) *Cement*

Cement mortars are too rigid and suffer from the defect of not adhering well to earth walls. Cracking, blow-up, and loosening in sheets are frequently observed symptoms. Their use is not advised and it can, at best, be a make-shift solution, with proportions of the order of 1 part to 5 or 10 parts. It is better to add a little lime to them: 1 to 1 or 1 to 2 if at all possible.

Cement renderings should be applied on a wire netting. This reduces cracking and breaking into slabs, but does not improve their adhesion.

(d) *Gypsum (plaster)*

Plaster renderings are fairly compatible with earth walls but should be used inside rather than outside. In dry climates, they can be used outside as well. It is best to improve the adhesion of plaster to the earth by first applying a diluted wash of lime or cement.

On outside walls slaked lime may be added to the plaster. This hardens the rendering and improves its water resistance. The rendering can be applied in two layers with 1 to 1.5 parts of slaked lime added to 10 parts of plaster and 7.5 to 10 parts of sand for the first layer. The same proportion of binder, but without sand, can be used for the second layer. Waterproofing the surface with a fluorosilicate solution after a period of a few days is desirable.

(e) *Pozzolana*

Added to lime, pozzolana, which contains enough silica, produces a compound similar to Portland cement. Pozzolana-based renderings are, however, far more flexible than cement-based ones. They are often used for finishing flat earth-brickwork roofs and for vaulting.

(f) *Gum arabic*

When added to soil, or even better to sand, gum arabic produces good protective coatings, which are hard, do not crack, and adhere well to earth walls. This product does not stand up well to water and it is therefore better to use it on the inside of the building. The colour

obtained is a pastel red ochre. Gum arabic is used as a rendering chiefly in Sudan, but is becoming increasingly expensive.

(g) *Resin*

As knowledge stands at present, the use of resins, organic binders, and various mineral substances should preferably be limited to finishing the renderings described above.

(h) *Ready-to-use renderings*

These renderings are prepared with an added dry mortar based on mineral binders. They are designed to be applied to other supports than earth walls. Their use demands technical and strict, systematic experimentation.

Combined systems, such as mineral-organic products with an impregnation layer, finishing mortar based on mineral binders to which resins are added, and finishing layers using organic binders, are also worth considering, on condition that the basic principles applicable to all renderings for earth walls are respected.

(i) *Plasticcoating*

The use of a plastic coating implies that the appearance of the support will not be preserved. The incorporation of reinforcement in waterproof plastic protection may be attractive, and depends on the configuration of the support. However, the danger of blistering and the impermeability to water vapour makes their use inadvisable.

## 2. Output and cost of plasters

The following figures are based on observations on large-scale sites in tropical countries. The outputs given are for qualified labour.

Preparation of the support, scraping and removal of dust	1/2 h per D per m <sup>2</sup>
Preparation of the mortar + assistance to the mason	1/4 h per D per m <sup>2</sup>
Application in 3 layers by the mason	1/4 h per D per m <sup>2</sup>
Application of wash by 1 labourer	1/30 h per D per m <sup>2</sup>
Supervision by a foreman	1/20 h per D per m <sup>2</sup>
Total	1.1 h per D per m <sup>2</sup>

Cost is not particularly dependent on the type of rendering but rather on the organization of the work. The following figures are for



work carried by direct employees or by a cooperative. They are applicable for various sites and for both interior and exterior rendering.

Type of structure	Percentage of total cost without services
1. Very-low-cost house	15
2. Small house with a minimum of equipment	20-25
3. "Carcase" dwelling	30
4. Covering for vaulting and domes	5

For type 1, the 15 per cent includes any incorporation of wire netting. The final price can be broken down as follows: materials 8 per cent; equipment 8 per cent; organization 8 per cent; pay 76 per cent. Labour costs can in fact reach 80 or even 90 per cent.

For type 2, a minimum of equipment means no electricity, a single tap, a minimum of rooms, no floor protection, no drop-ceiling.

In type 3, the indicated value of 30 per cent is not unreasonable even when the dwellings are no more than carcasses.

In type 4, the covering is a dampproofing coat.

### C. Earth renderings

Earth can undoubtedly be an excellent rendering or be one of the ingredients of a rendering. Even so, earth is not a satisfactory basic component for first-class exterior renderings, particularly in rainy environments, unless it is improved by the use of a stabilizing additive. Earth renderings have been widely used and still are in many regions of the world.

The adhesion of earth renderings, whether used inside or outside, is virtually perfect. They are, however, a wearing layer which is the first affected by erosion and which can be cheaply replaced. The simple application of impregnation, a wash or grout, or paint can considerably improve these renderings, which are somewhat fragile. The earth rendering is often referred to by the term *dagga*, and the widespread employment of the term in the literature often leads to confusion.

#### 1. Earth

When used as a rendering, the earth is first rid of all elements of a diameter greater than 2 mm. Clayey and sandy soils will preferably be used (1 part of clay to 2 to 3 parts of sand). Preliminary tests are

advisable in order to determine exactly what value should be given to the 2 to 3 parts of sand. Such tests examine cracking and adherence a few days after application. Clays which suffer from strong swell and shrink are not suitable. Clays of the kaolinite type are preferable.

Lateritic clays often make good rendering in an attractive red or ochre. The main drawback of these earth renderings is that they are susceptible to cracking.

## *2. Water*

No great problems with mixing water are encountered. The most crucial factor is the amount used, which is important in controlling the shrink and drying of the rendering. Observation has shown that it is best to use rainwater.

Other improvements are also possible by adding deflocculants and dispersants to the water. By using less water and obtaining a dispersed and highly uniform mixture, the rendering will be less subject to shrink and thus will dry more quickly. The main deflocculants are sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) and sodium silicate ( $\text{Na}_2\text{O}_x\text{SiO}_2$ ). Between 0.1 and 0.4 per cent should be added to the clay. Other products such as humic acid, tannic acid and horse urine can replace the water entirely.

## *3. Fibres*

Fibres act as reinforcement. Fibres can be of many different origins; vegetable, such as straw from wheat, barley, winter barley, rice or millet; animal hair and fur; or synthetic, such as polypropylene fibres. Common proportions are of the order of 20 to 30 kg of fibres per  $\text{m}^3$  of soil used. In the majority of earth renderings so reinforced, the fibres are cut to fairly short lengths.

The finishing layer can also be reinforced with fibres which gives an attractive texture to the rendering but which traps dust.

Some fibres, such as wood shavings or sawdust, can also be added as a light filler. Wood-waste fillers should, however, be first mineralized by soaking in milk of lime or a cement solution.

## *4. Stabilization*

Virtually all products used for stabilizing soil in bulk are suitable for preparing renderings.

### *(a) Cement stabilization*

This is only really effective if the soil is very sandy. Proportions may vary from 2 to 15 per cent of cement, depending on whether a mild improvement or true stabilization is desired.

Cement-stabilized renderings should by preference be applied to stabilized surfaces.

It is also possible to add between 2 and 4 per cent of bitumen. This mixture tends to darken the dressing without spoiling the colour, but greatly improves water-resistance.

#### (b) *Lime stabilization*

Lime stabilization has its greatest effect on clayey soils when it is used in large quantities, often over 10 per cent. Similarly, a lime-stabilized rendering is best applied to a stabilized surface.

The addition of animal urine or dung can have truly astonishing effects on the rendering (less shrink, greater hardness and good permeability). The main drawback is the strong ammonia smell during mixing, which may upset some people.

#### (c) *Bitumen stabilization*

Bitumen-stabilized soils should be neither too clayey nor too sandy and dusty. The quantity of bitumen ranges from 2 to 6 per cent. They are usually cut-backs which should be heated without exceeding 100°C. Where bituminous emulsions are used the mixture must be made slowly in order to avoid any breakdown of the emulsion.

The stabilizer can be prepared by adding four parts of bitumen to 1 part of kerosene, followed by heating and adding 1 per cent paraffin wax. The kerosene can be replaced by coal creosote. The mixture described above can be replaced by 4.5 parts of cut-back or 3.5 parts of bitumen emulsion.

Bitumen stabilization for renderings is particularly effective on soils which have already been reinforced with straw or even with dung. The bitumen is added only at the end, two to three hours before the rendering is applied. Mixtures of asphalt, gum arabic and caustic soda solution are also highly effective.

The support should be properly prepared, brushed and moistened. Excellent results have been obtained with this type of rendering by the Central Building Research Institute (CBRI) at Roorkee in India.

#### (d) *Natural stabilizers*

These are highly diverse and are considered as traditional stabilizers in numerous countries. Their effectiveness is extremely variable. Their effect is more the retarding of the decay in the material, without really ensuring the sustained lifetime of the rendering, but reducing the frequency with which it is remade.

Traditional stabilizers include the juice of the agave and the opuntia cactuses, melted shea (*karité*) butter, often added to gum arabic; the juice from boiled banana twigs; 15 litres of rye flour boiled in 220 litres of water, with the paste obtained being added to the soil; cowpats or horse droppings (1 part dung to 1 part clay and 5 to 15 parts of sand); gum arabic, which forms colloids with water; the sap of the fruit of the *acacia scorpiodes* boiled in water with several pieces of limonite (a type of laterite), which results in a rather effective water repellent; euphorbia



latex precipitated with lime, the sap of the *néré*; and Peulh soap, a sort of casein, thinned and beaten like a paste. Other natural products have been tried at the Cacavelli Centre in Togo for the improvement of renderings. These include kapok oil obtained by roasting kapok seeds to obtain a powder form with a high lipid content. The powder is diluted with water and boiled for several hours. This is then mixed dry with the water, mixing water being added subsequently. The rendered wall is then distempered with two coats of kapok oil. Calcium palmitate, obtained by mixing fat lime and palmitic acid - a product obtained by reacting HCl with a native soap known as *akoto* can also be used. The calcium palmitate is diluted in a small volume of water and the soil is mixed with the milk of lime obtained (10 per cent by weight of the mixture). The Hausa of Africa use natural potash, or an infusion of carob-bean husks, or even of mimosa which the richest people import from Egypt. In addition to the above, there are a great many other natural products which could be used as stabilizers in rendering earth walls.

#### (e) *Chemical stabilizers*

There are numerous chemical stabilizers and their effectiveness has as yet not been scientifically confirmed. These include the celluloses, polyvinyl acetate, vinyl chloride, the acrylics, sodium silicate, the quaternary amines, aniline, bentonite, soap stearates, casein glues, and paraffin. Others may be combinations of the above with, perhaps, the addition of some natural products.

### *5. Application of earth renderings*

When used indoors earth renderings give excellent results, although it is advisable to strengthen weak points of the building with a mortar of sand and lime (internal and external corners, reveals, the bottom of walls).

When used outside, a single layer would not be enough. At least two layers should be applied, and preferably three. First, apply a rough-cast in a highly adhesive clayey soil which can be finished with a mortar consisting of one part lime and one part sand; followed by a 1.5-cm-thick layer of pargetting in clay soil and coarse sand, reinforced with fibres chopped to 3 to 5 cm long, and finished with a top layer in clayey soil and sand, to which a light filler has been added (e.g., chaff or flax).

#### *D. Paints and sealers*

##### *1. Opaque paints*

The range of commercially available paints is extremely wide. When ordinary paints are used to protect earth walls they give satisfactory results at first. Very quickly, however, deficiencies such as blisters and

loss of adhesion become apparent. Thus paints cannot be regarded as a means of giving a soil wall a lasting finish. Nevertheless, they afford temporary protection pending proper repair. Their use can be permitted to indoor and outside walls which are very well sheltered from attack from the climatic environment. Even so, it is preferable to use them as a complement to the finishing layer of the rendering. The surface which is to be painted should be absolutely dry and all the dust removed with a brush. Moreover, primers which penetrate deeply into the material give poor results. It is better to apply an impregnating layer, either in linseed oil, or in a very dilute lead-based paint, applied at a rate of 0.50 l per m<sup>2</sup>. When applying the two finishing coats, the best course is to consult the paint manufacturer for technical advice.

When walls are stabilized in bitumen, it is advisable to apply two to three layers of paint to avoid bitumen exudations.

When all conditions are favourable, i.e., good-quality paint, proper preparation of the support, and good application, the paint may last between three and five years.

American experiments have shown that better results are obtained on sandy earth walls rather than on clayey ones.

#### (a) *Industrial paints*

Aluminium-based paints do not hold well when applied directly to earth. They may be applied to undercoats treated with bitumen or to bitumen-stabilized walls.

Casein-based paints give fairly satisfactory results on earth walls.

Primers can be used to impregnate the surface.

Lead-based paints can be used on a surface treated with linseed oil.

Oil-based paints perform only moderately.

Polyvinyl acetate emulsions can sometimes be satisfactory.

Water-bound distempers should not be used on crumbly walls.

Latex paints are quite efficient on stabilized soil walls.

Resin-based paints often give satisfactory results, but silicon paints are not very reliable.

Acrylic paints breathe, are elastic and water-repellent, and stand up well to the alkalinity of earth walls.

Watertight paints, alkyds, epoxies, and polyurethanes are to be avoided because they retain moisture.

Chlorinated rubber-based paints, which are elastic, and stand up well to heat, ultra-violet radiation and atmospheric conditions, can be used to waterproof roofs but should not be used for soil walls.

#### (b) *Oils*

Earth walls are an extremely porous support and absorb large amounts of non-oxidizing oils, such as sump oils. However, they do not perform satisfactorily as the impregnated layers should not go too deep.



Linseed oil oxidizes, reacts with air and becomes fixed. It is only slightly soluble in water and can be applied to moist soil. It is a very satisfactory primer for lead and oil paints, but is expensive.

Castor oil has the same properties but is scarce and very expensive. It may be that fish oil is equally good.

Palm and shea oils have both been studied in Côte d'Ivoire but suffer from the fact that they are very viscous, making them difficult to apply, and giving rise to efflorescence.

#### (c) *Plant juices*

The juice of the *euphorbia lactea* is very well known in tropical countries. It can be used to protect earth walls but it is absolutely essential to add it to lime (precipitation). The juices of the agave and opuntia cactuses can be used but they are extremely poisonous and can harm the eyes.

In Benin, Burkina Faso and southern Ghana a red plant extract known as *am* is employed. In northern Nigeria *iaso* is used, which is an extract from a local vine called *dafara* (*vitis pallide*). *Makuba* is also used, this being an extract from carob-bean husks.

Banana juice can be used, but it must be boiled for a long time, consuming large amounts of fuel in the process; and there is no guarantee of it being effective.

#### (d) *Other natural products*

Paints can also be made from cream cheese (six parts) mixed with one part of quicklime and greatly diluted in water, or from whey, with 4 l of whey added to 2 kg of white cement. These formulations have been developed by the University of South Dakota.

#### (e) *Soil*

Earth slurries can be used indoors and fixatives added to them. Outside they are not lasting, but can be improved by stabilizing with mineral binders (lime, cements) or organic binders (bitumens, plant juices, and various oils), or with acids. Even when improved these emulsions must, in general, be regularly refreshed.

### 2. *Transparent products*

There is a strong trend towards the employment of products which aim at conserving earth indefinitely, while preserving the appearance of the material. Unfortunately, earth is a support that is very different from other industrial materials, and the results obtained with these "magic" products are, to say the least, random, as real conditions are not the same as those in the laboratory. Numerous problems appear after a period of years.

The chemistry and the composition of the products are highly complex. It is advisable to carry out preliminary tests with a view to



ensuring their effectiveness, at least in the medium term and for fairly harsh outside conditions. Many of these products, described as "totally waterproof", can resist only a low pore water pressure. Generally speaking, such transparent products help to reduce the deterioration of the wall at the wearing coat. Their quality depends on the depth of penetration (up to at least 2 cm). These products may form a crust of treated soil, which has the effect of producing the disaggregation of the wall. This happens with sodium silicate and silicones in general.

With knowledge of these products - whether based on paraffin, wax, resin, or various minerals - as it stands, their use is best limited to a treatment of the finishing course of thick renderings and on sheltered walls.

#### (a) *Surface water repellents*

Silicons in a volatile solution require a suitably dry surface and their use is limited by the size of cracks, as these may not exceed 0.15 mm, especially on exposed walls. The only use for which they should be contemplated is for finishing renderings.

Silicons in an aqueous solution or emulsion can accommodate themselves to a certain moistness of the support, although the same reservations must be made as above.

Metallic soaps, stearates, and polyoleofins must first be made the subject of special attention.

Fluates, or more scientifically fluorosilicates, form an artificial calcine by reacting with calcium carbonate. They have absolutely no effect on soils stabilized with lime. They may be used with good effect on carbonated renderings using lime mortars.

#### (b) *Resin-based film-forming impregnation treatments*

These may offer an attractive solution for sheltered outside walls if they can be strongly absorbed into the first few centimetres of the soil and if they do not form a thick surface crust. Checks should be made to ensure that permeability to water vapour is maintained and that the impregnation can be refreshed.

#### (c) *Water-proofing coatings*

These products are based on resins in an organic solution or dispersed in water. Their efficiency is limited by cracks which may exist or appear in the support. The risk of blistering and deficiencies in permeability to water vapour makes their use highly unpredictable. They should in principle be avoided.

### **E. Whitewashes**

Limewashes made from non-hydraulic lime have been widely used in many regions since time immemorial. They represent a fairly cheap way of affording protection against the harmful effects of rain,

particularly in the absence of sophisticated materials and where budgets are subject to severe restrictions. These limewashes are most suitable for affording protection indoors or on sheltered walls outside. They can, however, be easily improved so that they last several years.

### *1. Drawbacks*

Limewashes are not particularly durable because they are easily washed off. They must be refreshed periodically (once or twice a year), particularly in wet climates. Additives can make very significant improvements to them. These include vegetable drying-oils (linseed oil, nut oils, castor oil, cotton oil, and hemp oil), glues, casein, salts which are more or less hydrated (zinc sulphate, potassium alum, sodium chloride), resins or oleo-resins and rubbers or water-soluble rubber resins. Such limewashes are also very sensitive to mechanical shock and only offer limited protection to abrasion.

### *2. Benefits*

Limewashes made from non-hydraulic lime are cheap and stand up fairly well to alkalinity as well as bitumen exudations (on walls stabilized in bitumen). Light in colour, they reflect solar radiation. They can easily be tinted with oxides. They can be easily and quickly applied and do not require specialized labour, although they must be applied with care.

Refreshing them is easy and their ageing causes no major deficiencies in the support. The periodic refreshment rejuvenates the structure.

They have the advantage of regulating the moisture balance between the support and its surroundings. Because of their constituents (quicklime or slaked lime, salts, formaldehyde), they have certain antiseptic properties. They bring light and hygiene to what would otherwise often be miserable and unhealthy slums.

### *3. Binder*

The best results are obtained with non-hydraulic lime slaked in paste, using high-yield, finely sieved quicklime. The wash is prepared a few days before application. Commercial slaked lime can also be used on condition that it is not too far in carbonation. The content of calcium and magnesium oxides should not be lower than 80 per cent, while the carbon dioxide content should not be higher than 5 per cent.

### *4. Preparation of the binder*

The containers or trenches used for slaking quicklime should be considerably larger than the original quantity as the material increases greatly in volume (as much as double). Attention should also be paid to the risk of burning as slaking quicklime generates high temperatures (120° to 130°). The operation is best carried out at night when it is cool, with plenty of clean water available. All lumps are broken up and the



lime mixed well until a uniform paste is obtained, which is brought to the desired consistency by adding suitable amounts of water. If slaked lime is used, the quality of the sieving should be checked. The basic mixture is one volume of slaked lime to one volume of water. It may be necessary to add water to obtain the desired consistency.

### 5. Application

The limewash is applied to a clean, dust-free surface, which should be free of all crumbling, in at least two coats (three or four coats being preferable). The first coat will be thin, but subsequent coats will be increasingly thicker. A distemper brush can be used for the first coat, while for the second coat a broom can be used, and even a yard brush is suitable for the later coats. The distemper is applied when the wall is in shadow and extremes of heat or cold should be avoided. Precautions should also be taken to avoid showers, which could wash the whitewash off the wall. The best method is *alfresco* but this is very difficult to carry out on earth walls. Application to the dry surface will thus be the most common method used and care should be taken to moisten the surface, preferably with clean milk of lime, but without soaking the surface. Excessively thick coats will flake off. Drying should be slow.

### 6. Simple test

A block is weighed in advance and then given two coats of limewash. The block is immersed in water for two days and then weighed again. If the difference in weight is of the order of a few tens of grams the limewash is good. If the difference is of the order of several hundred of grams the limewash should be rejected.

### 7. Fillers

Fillers are additives to the binders which give the limewash properties which the binder alone could not give it. The fillers discussed below are all compatible with lime.

#### (a) Linseed oil

This increases the ability of the whitewash to stand up to variations in humidity and improves adhesion to the support. It should be added immediately before application.

#### (b) Tallow

This is animal fat composed of glycerides which gives greater plasticity when applying the limewash, by increasing water resistance and adhesion. Add about 10 per cent by weight of molten tallow to the lime. Tallow can be replaced by calcium stearate or linseed oil.



(c) *Skim milk or whey*

This increases the impermeability of the limewash. Add 1 part of 10-day-old skim milk or whey to 10 parts of water used in the preparation of the whitewash, immediately before use.

(d) *Casein glue*

In powder form, this is known as "cold glue". It acts as a fixative. The addition of formalin increases its strength. Dissolve this glue in boiling water until it becomes soft (2 hours) at the rate of 2.5 kg of glue to 7 l of water.

(e) *Animal glues*

These improve the adhesion of limewash. They include glues made from skin and from bones.

(f) *Rye flour*

This forms a vegetable glue soluble in warm water. It requires the addition of zinc sulphate as a preservative when it is in paste form. It increases surface hardness and resistance to rubbing.

(g) *Alum*

This is the double sulphate of potassium and hydrated aluminium. A small quantity in the form of a paste made by grinding and then boiling in water for a period of one hour is added to the wash immediately before use. It increases workability, surface hardness and resistance to rubbing.

(h) *Sodium chloride*

Common salt, it retains moisture in the limewash and facilitates the carbonation of the lime. It should be added slowly to the limewash prior to use. Calcium salts and trisodium phosphate ( $\text{Na}_3\text{PO}_4$ ) are also used.

(i) *Formaldehyde*

This has the antiseptic and stabilizing properties of urea-formaldehyde. Dissolve it in water and add it slowly to a mixture of lime and casein glue or lime and  $\text{Na}_3\text{PO}_4$ . It does not keep well.

(j) *Molasses*

This is a syrup residue remaining after the crystallization of sugar. 0.2 per cent by weight added to lime speeds carbonation and increases strength.

(k) *Mineral fillers*

These are inert fillers or soil (kaolin).

(l) *Colourings*

Exclusively minerals, in the form of moistened powders, they should be added prior to use.

## *F. Slurries*

### *1. Cement-washes and hydraulic lime-washes*

Simple washes of cement or hydraulic lime give good protection and improved durability to earth walls. They are generally feasible when little money is available. They are not affected by the alkalinity of the wall. In good conditions of execution, they can help to reduce the quantity of stabilizer in the bulk of the wall. This type of wash requires a humid environment when hardening and thus curing must be carefully supervised.

They are more difficult to apply than the lime-washes based on non-hydraulic limes. As cement and hydraulic lime are more finely ground than non-hydraulic lime, the water requirement should be reduced, with a cement/water ratio of the order of 1 to 1.5 compared with 0.78 for non-hydraulic lime. As a result, workability and covering capacity are less.

These washes are fairly resistant to the passage of water vapour and are, therefore, only suitable for use in regions where water vapour migration from the inside to the outside is not a problem (i.e., they are excellent in sub-tropical regions). They have a limited lifetime, between 5 and 10 years (on stabilized walls), and therefore require periodic refreshment.

Paints based on coloured cements also exist. These paints, which contain additives to improve their plasticity, are only suitable for walls in stabilized earth and for very strong walls, but even here the results are rarely satisfactory. On weak walls, cement paints should not be used because of flaking and blistering.

Generally speaking, when it is intended to give stabilized walls a cement-wash or hydraulic lime-wash finish, they should be prepared with care (holes and cracks filled, dust removed) and thoroughly wetted. This moistening is indispensable when the mixture contains no calcium chloride (a salt which retains water), the use of which is justified in hot and dry regions (not more than 5 per cent of the mixture). Moistening facilitates application and prevents excessively rapid hydraulic shrink but may reduce the impermeability of the wash. The addition of hydraulic lime to the cement (maximum 25 per cent) does nothing for the wash but makes application easier due to improved plasticity.

Washes in cement or hydraulic lime should be applied in at least two coats, each 1 to 1.5 mm thick. Three or four coats are even better. The first coat should be applied with a brush that is not too hard, while subsequent coats can be applied with a broom or spray-gun.

If the surface is smooth, a thinned coat should first be applied to serve as a size or primer for a subsequent thicker coat. The reverse applies if the surface is rough. The wash should be applied when the wall is in shadow. Once the last coat has dried, it should be moistened



in order to hydrate the cement and moistened again just before nightfall. The second coat is best applied at the earliest 12 hours after the first; and if at all possible 24 hours later, after moistening the first coat again.

Washes should be used within two hours of their preparation. Left-overs should never be used on the following day.

Colourings (3 to 7 per cent of various oxides) or water repellents can be added, though this should be done in the last coat. The water repellent can be 2 per cent of calcium stearate solution added to the cement, or 2 per cent of copper sulphate solution in a concentration of 100 gm to 10 litres of water.

A poorly applied cement-wash to a badly prepared wall will have the tendency to peel, flake, blister, and lose all its protective power, not to mention the shabby appearance it will give to the building.

Two formulations may be considered:

(a) One hundred parts of Portland cement should be mixed with 50 parts of silica sand or any other hard fine sand. Calcium chloride should equal 4 per cent of the quantity of calcium stearate equal to 2 per cent by volume of the cement. The sand is mixed in after first mixing the cement, the calcium chloride and the calcium stearate. The volume of water is more or less equal to the volume of cement, although this may vary according to site conditions.

(b) Slurry made lateritic soil, cement and water (Côte d'Ivoire). Two 50-l barrows of lateritic soil and one bag of cement are mixed with 175 l of water. The slurry covers at a rate of  $2.5 \text{ kg per m}^2$ , or in other words  $340 \text{ g of cement per m}^2$ : this is very economical.

## *2. Bitumen washes*

Perfectly dry earth walls with wellprepared surfaces (harshness rubbed down, brushed, and dust removed) can be protected by a coating of bituminous products such as emulsion, cut-back, "Flintkote", and so on. Local climatic conditions are very important as these products are more or less impermeable to water vapour. Moreover, the effectiveness of bituminous products for surface treatments is not very prolonged and care must be taken to ensure that periodical refreshment is carried out. Nevertheless these bituminous washes are among the least expensive and greatly improve the resistance to water erosion and surface abrasion of earth walls.

A precondition to the success of these bituminous coatings is the dryness of the ground to which they are applied. If the ground is moist, blisters and bubbles will soon appear leading quickly to the detachment of the coating and, even worse, the loss of material.

Bituminous coatings are often resisted because of their sombre colour - black. This drawback can be cured by treating them with a finish. This finish may be coats of paint or cement or lime-based washes. Such finishes should be applied several months after the treatment of the bitumen wall so that any defects in the bitumen coating become



apparent and in order to avoid bitumen exudations. Applications of a paint finish, particularly oil-based paints, to a bitumen-stabilized wall or a wall which has been given a bitumen coating, must be preceded by the application of an undercoat of bitumen-based aluminium paint. This paint is compatible with the emulsion of the wall: the flakes of aluminium in the paint spread and cover the wall, preventing any exudation of bitumen from the wall.

Other treatments which can be immediately applied can also be considered. These include sanding with washed sand on the fresh bitumen coating.

Study of these finishes for bitumen-stabilized walls has shown that generally speaking products applied with a brush, such as milk of lime, bitumen emulsions, polyvinyl acetate, and styrene emulsions, remain highly permeable to water but hold back bitumen exudation.

Distemper paints and alkyd emulsions are not advisable. Oil-based paints stand up well to water but not to exudation. Bitumen paints are satisfactory from both points of view.

Three formulations may be considered:

(a) Paint based on coal-tar: one volume of Portland cement, with one volume of petrol, and four volumes of coal-tar. The tar does not have to be preheated. The cement and paraffin are mixed first and the tar is then added to them. The mixture is applied with a coarse brush to a fine primer coat made of a mixture of water and gas tar. The colour is black.

(b) A liquid bitumen wash can be produced from two volumes of coarse benzol and one volume of bitumen dissolved in the benzoline, to which a small amount of resin and quicklime has been added. Apply with a brush or fine spray. This wash gives a brown colour.

(c) A wash can also be prepared from 25 kg of preheated asphalt and 50 l of petroleum oil. The asphalt is added little by little to the oil and carefully mixed until totally dissolved. Once the mixture has cooled, it is poured through a fine strainer into another container in order to eliminate any undissolved materials and foreign bodies. It can be applied with a pesticide spray at a rate of  $100 \text{ m}^2$  per day per person. The colour is dark grey. A finishing coat in milk of lime to which an animal glue has been added gets rid of any undesirable colour.

### III. DETAILED ASPECTS OF SURFACE PROTECTION

SUPPORTS					
MONOLITHIC			BRICKWORK		
SMOOTH LIKE RAMMED EARTH	POROUS LIKE COB	VERY POROUS LIKE STRAW- CLAY	SMOOTH LIKE BLOCKS	POROUS LIKE ADOBE	VERY POROUS LIKE SOD
1	2	3	4	5	6

#### *A. Lathing and anchoring*

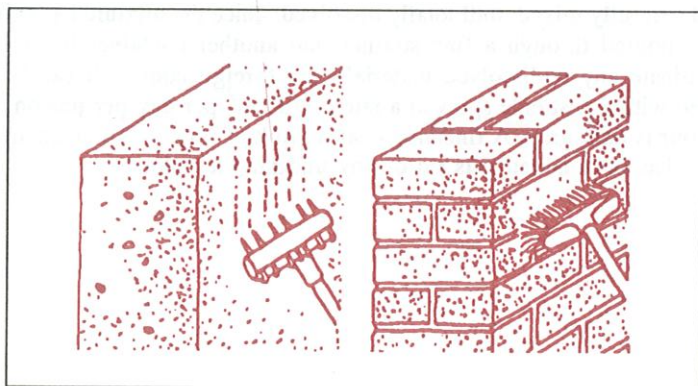
##### *1. Glue*

(Supports 1, 2, 4, 5)

The use of white joinery glue (dilute polyvinyl acetate) has been tested in Egypt, Nigeria, Sri Lanka and Sudan. This glue, diluted in water, is applied in two layers using a brush. Dust is fixed and the adhesion of the mortar of the rendering is facilitated. This glue surface treatment should, by preference, be used in conjunction with a fibre-reinforced rendering. Other dust fixatives can be used if they are compatible with the rendering.

##### *2. Scraping and dust removal*

(Supports 1, 2, 4, 5)

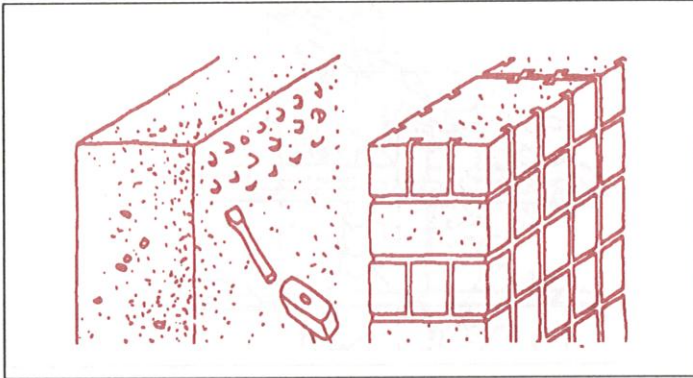


Scraping the supports is particularly important where they are at all crumbly, as this makes it possible to remove any materials lacking cohesion or which are not well fixed. On rammed earth, this exposes

the sand and gravel skeleton holding the rendering. Dust removal is indispensable on the majority of earth supports. It can be done with a brush, when dry or when moist (without saturating the wall) or using compressed air blowers.

### *3. Grooving*

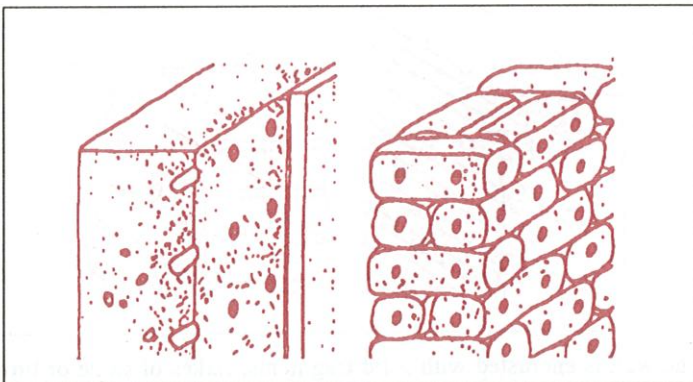
(Supports 1, 2, 4, 5)



On walls built in compressed blocks and adobes, the joints are scraped to a depth of 2 to 3 cm and the rendering is anchored by the hollowed-out joints. The blocks can themselves be grooved or chiselled. Grooving is a good way of ensuring anchoring on rammed earth and cob. The grooved surface can also be prefabricated with special moulds for blocks and formwork fitted with nailed, dovetailed battens for rammed earth.

### *4. Holes*

(Supports 1, 2, 3, 4, 5, 6)



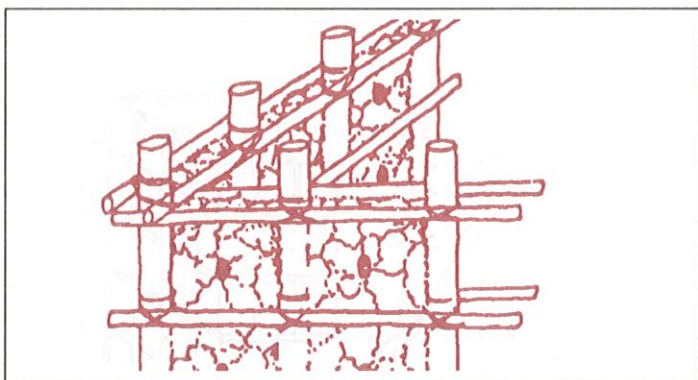
This anchoring technique is particularly suitable for rammed earth, cob and straw-clay supports. It involves making slanting holes when the



material is still moist or the formwork has just been removed. The holes should be at least 3 cm and preferably 6 cm deep. When building in balls or loaves of soil, the holes are made in the fresh material.

### *5. Piercing walls*

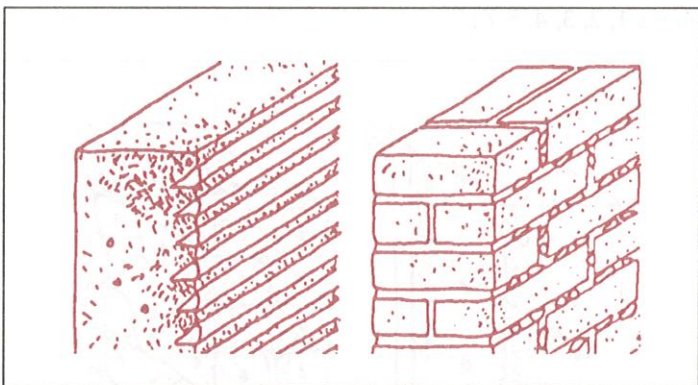
(Supports 2, 3)



This procedure is used in Gabon on houses built in cob between posts. The masses of a clayey soil covering the netting are pierced with a dagger from one side to the other. The rendering is applied on both the inside and the outside and the two layers are united by a sort of bridge of rendering.

### *6. Anchor points*

(Supports 1, 2, 3, 4, 5, 6)

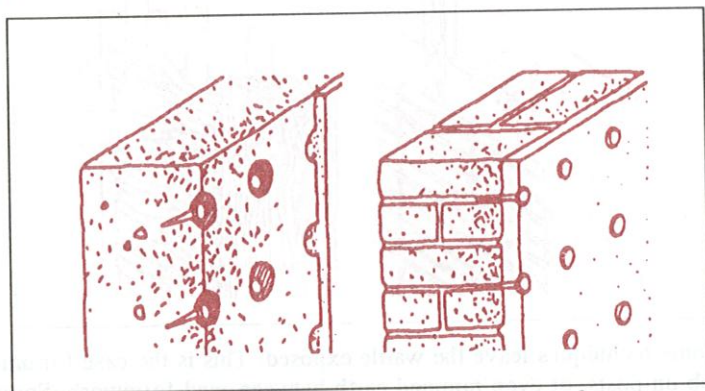


The wall is encrusted with solid fragments, flakes of stone or broken pottery. This encrusting can be easily carried out on fresh cob, or even on daub. The fragments are set obliquely. On blockwork or adobe walls, the fragments are inserted into the fresh mortar.

Anchoring points of the same composition as the rendering can also be provided, e.g., strips of lime included in outer thickness of rammed earth.

### *7. Nailing*

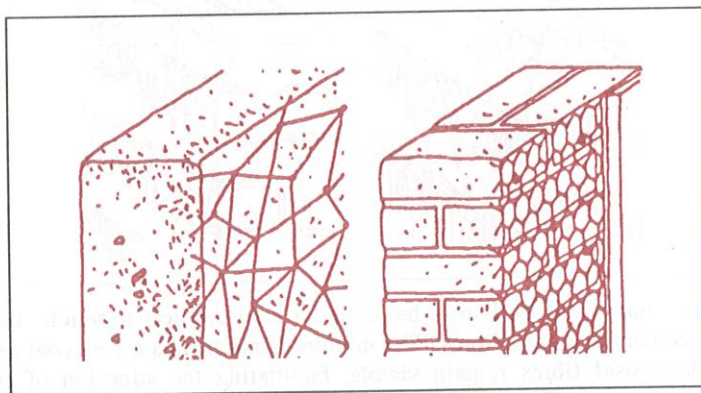
(Supports 1, 2, 4, 5)



The nails should preferably be galvanized and long (at least 8 cm), with wide flat heads. They are inserted in the wall in a regular pattern, with about 10 to 15 cm between each nail. As they can hinder the application of the rendering, another method is to make holes in which the nails are placed so that they are level with the support, or to insert the nails after the application of the floating coat.

### *8. Lattice work*

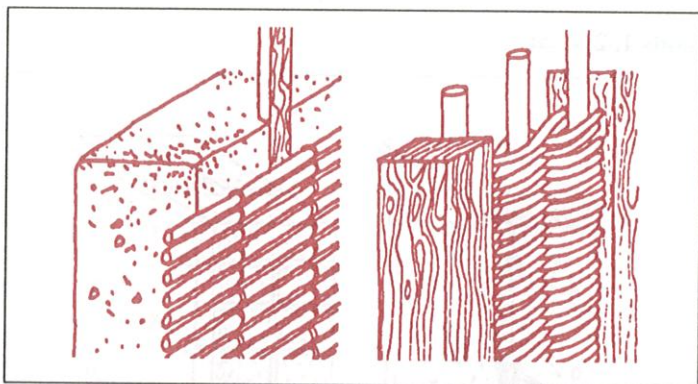
(Supports 1, 2, 3, 4, 5, 6)



Conventional chicken wire can be used (hexagonal holes). It is best if the netting is galvanized for walls exposed to weather, although non-galvanized netting adheres better. The netting is fixed by nails

twisted into the mesh and nailed in a regular triangular pattern. Steel wire can be woven on to nails driven into the wall.

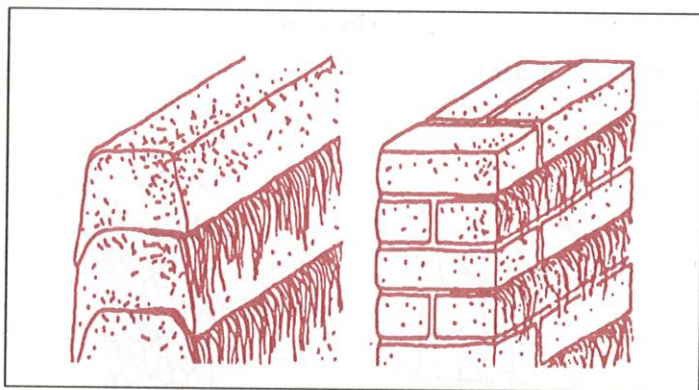
### 9. Wattle



Some techniques leave the wattle exposed. This is the case for daub or cob on posts, or even rammed earth between reed formwork. Sometimes this is also done with heavy clay-straw, which is covered with plaited canes or woven reeds to anchor the rendering.

### 10. Fibres

(Supports 2, 4, 5)



The University of Nairobi has tested a wall protection which combines cement and sisal fibres. The mixture is applied as a first coat and the short sisal fibres remain visible, facilitating the adhesion of the subsequent coats. Instead of sisal, other natural fibres (coir, hemp, etc.) synthetic fibres (polypropylene), animal hair, or woven materials (jute sacking) can be used.



## *B. Finishes and decorations*

Apart from their function as wall protection, both indoors and outdoors, surface coatings play a decorative architectural role. This aspect of the rendering in finishing and decorating buildings is apparent in many countries and has long been exploited. It includes customary techniques and motions just as much as the texture or grain of the finishing coat, reliefs worked in the bulk of the wall, colour, and flashing with various other materials. Finishes of the visible rendering are applied manually, either with traditional masonry tools, trowel, hawk, drag, etc., or mechanically with blowing machinery.

The various treatments are carried out either before hardening (float-finished or rustic renderings), or after hardening (e.g., scraped or glazed renderings).

### *1. Smooth finish*

This is usually used indoors. The finish is smoothed with the laying-on trowel and the float.

### *2. Dragged finish*

The floated surface is scraped after hardening with a metal blade, or with a devil float, (i.e., a float with steel nails protruding from its bottom). Once the rendering is dry, the dust can be removed with compressed air or by hosing down.

### *3. Rustic finish*

The rendering is applied by the trowelful, each covering the previous one. When slapped on with the trowel the rendering has a scattered irregular grain.

### *4. Graining finish*

The rendering has a rough appearance resulting from being thrown or blown on (Tyrolean, fine sand, or plaster blowing equipment). This method reduces cracking.

### *5. Crushed rustic*

The wall is first given a grainy finish and then crushed with a float or flattening tool.

### *6. Whipped finish*

The freshly applied rendering is whipped with a broom or with flexible fibres (e.g., palm weeds).

### *7. Aggregate finish*

Coarse sand, small stones, stone chippings, or shells are thrown against the fresh rendering. The pebble dash finish is well-known for its ability to reduce cracking.

## IV. TESTS ON RENDERINGS

Numerous standardized tests exist which attempt to test the quality of renderings, and especially the behaviour of the inseparable support-rendering complex. The object of the tests is thus basically to find a rendering the behaviour of which will be acceptable, in time, for a specified support and in relation to a number of performance criteria selected by the user (e.g., frequency of maintenance, resistance to climatic and mechanical agents).

### *A. Small-scale tests*

These tests can be useful but are of limited application because they do not consider the rendered wall as a whole and concentrate on fragments.

#### *1. Open porosity*

First of all, the sample is dried by dry air or stove until it attains a constant weight. It is then completely submerged by any of various procedures and superficially dried with moist cloth and weighed. Porosity is expressed as a percentage according to the relationship:

$$\frac{P^1 - P}{P} \times 100$$

(where P = dry weight; and P<sup>1</sup> = absorbed weight of water).

#### *2. Moisture content*

This is measured either on the basis of the resistivity of the material with an apparatus equipped with two electrodes which are placed in the rendering, or with a sort of flat capacitor, which is applied to the rendering and gives a direct reading on a gauge.

#### *3. Absorption capacity*

Water is forced into the surface of the rendering under pressure. The quantity of water crossing a predetermined area during a given time is recorded by means of a flat chamber held in place by means of a waterproof putty and connected to a recipient of fixed level (in order to ensure constant pressure). A rendered block can also be completely immersed in water and the difference in weight before and after immersion determined.

#### *4. Erosion*

This test involves spraying with a jet of water or dripping water on to the material.

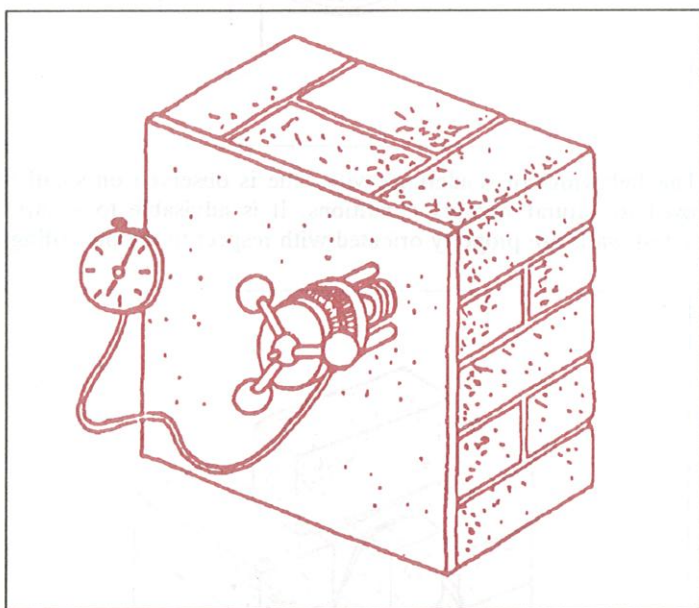
## *5. Adhesion tests*

Adhesion is measured by means of a dynamometer with gaiters which is used to tear loose a 50 mm pellet from the surface of the rendering after first cutting it free with a corer to a depth slightly more than that of the rendering. The pellet is glued to a metal disc with a suitable glue. Adhesion is good if breaking occurs in the rendering; it is not good if it takes place at the rendering-support interface.

Yet another test for the adhesion of rendering to rammed earth has been tried in Morocco. A porous cement block is stuck to a sample of rendered rammed earth, and tensile force exerted on a ring located in the axis of the block. The test is for an adhesion between rendering and rammed earth of 1 kg per cm<sup>2</sup>.

### *B. Large-scale tests*

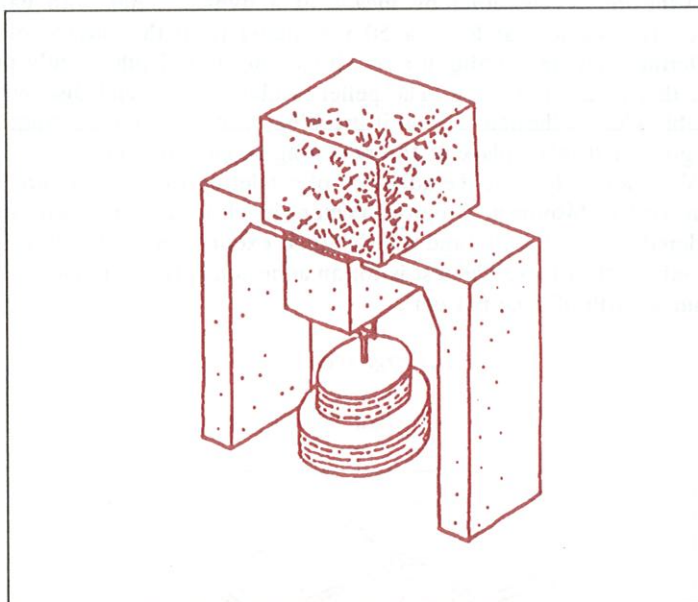
#### *1. Accelerated ageing*



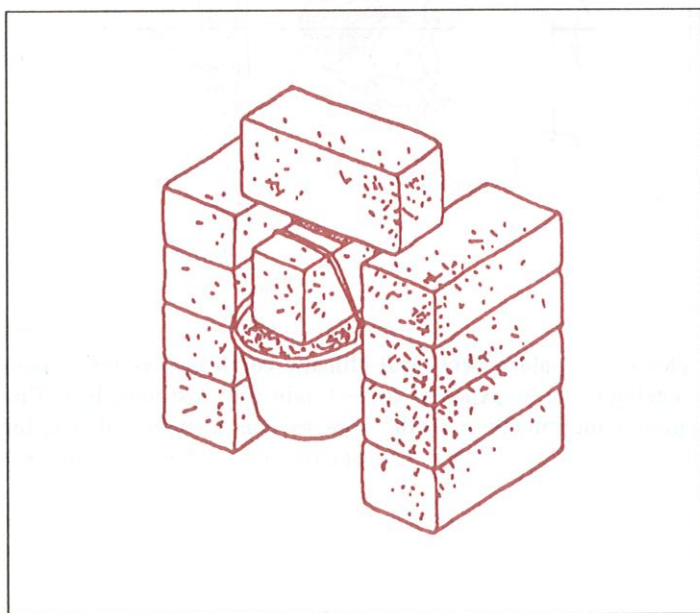
This test should reflect local climatic conditions as far as possible. The ageing cycle by exposure to heat, rain and frost must be defined by the proper interpretation of the tests as it is a matter of gauging the responses to stresses rather than determining a state after aging.



## 2. Natural ageing



The behaviour of renderings with time is observed on small walls exposed to natural weather conditions. It is advisable to ensure that these test walls are properly oriented with respect to the prevailing rain



and wind. This test has been tried in various countries, but has been carried out on a truly large scale in Senegal and in the United States and has been the object of study for several decades. Nevertheless the results are more accurate for perimeter walls than those of dwellings, as no examination can be made of the migrating water vapour which affects most renderings.

The test walls have a minimum exposed area of  $1 \text{ m}^2$ . They are subjected to the greatest climatic stresses in the region. They are covered with a waterproof cap projecting 10 cm on each side, and fitted with a drip. The test walls are separated from the ground by a footing at least 25 cm high and provided with anti- capillary barrier. The rendering comes to within 2 cm of the cap and reaches down to the footing, but does not touch it. At least one year and, more usually, two to three years, are required to arrive at the first conclusions which do not consider the disorders suffered at the edges of the test walls.

### *C. Building or building panels*

Natural exposure tests on buildings or building panels have been carried out in the United Kingdom, the United States, and several other countries. None of these buildings have ever been normally occupied and the differing orientations of exposure make comparison impossible.

In fact the best place for experimentation and observation is the stock of existing buildings.

## PART FOUR

# PRODUCTION OF COMPONENTS

### INTRODUCTION

Present-day earth construction employs production techniques ranging from the most rudimentary and artisanal to the most sophisticated, relying on industrial, mechanized and even automated processes.

Earth technology is no longer a matter of purely artisanal production or third-world techniques which offer no potential for development. The passage from artisanal to industrial production, although technically possible, must obviously be justified by the parameters governing each particular case, such as development policy, socio-economic and cultural considerations, economic and technical base, investment, work procedures etc.

For example, in craft production, five people can produce from 500 adobes (in West Africa) to 2500 adobe blocks (in Egypt and the Islamic Republic of Iran) per day, with no investment outlay being required. In industrial production in the United States of America five workers can produce up to 20,000 adobe blocks per day, but with an investment outlay of the order of \$300,000. Despite the current infatuation with mechanized systems, these are frequently unable to achieve qualitative and quantitative targets. The following remark by Joe Tibbets in the American magazine, *Earth Builder*, is worth quoting, "A machine is no better than the soil you put into it". It is not the machine that guarantees the quality of production but rather how production is organized and the skill of the operators. The real return of a mechanized production process is often only a tenth of what is commercially claimed for it, and a product that looks beautiful at a demonstration may be a sorry sight after a few years. The fact that earth construction is practised throughout the world dictates that an in-depth study of the tools of production be undertaken at all levels of the production process right up to the building and maintenance stages. Here we will limit ourselves to the three most frequently used of the 12 techniques discussed: compressed block, rammed earth and adobe.

Whatever the production methods, manual or mechanical, the operations involved are almost identical. This is particularly true for the excavation, transport, preliminary drying, and storage of the raw material, and the crushing and screening, proportioning and mixing, and drying and storage of the end product.



## I. THE PRODUCTION OF RAMMED EARTH

### *A. Preparation of the soil*

The soil used for rammed earth construction is characterized by its variable cohesion in the natural state. Production can be facilitated or complicated depending on the cohesiveness of the material. Moreover, while adobe or compressed block technology can tolerate some variation in soil quality - which can be compensated for by taking the appropriate measures in the production phase to ensure the quality of the structure - rammed earth technology is less flexible. The quality of a house built in rammed earth depends to a great extent upon the soil being of a consistently high quality. The raw material excavated from the borrow must meet this requirement for a material of a more uniform quality. In non-stabilized rammed-earth construction, builders must ensure that the earth to be used satisfies the selection criteria, and this in particular with respect to its texture and moisture content. This simplifies the entire production process, though this is not the case when other stages such as screening, pulverization and dry and wet mixing are necessary, for example, for cement or lime stabilization. Too wide a departure from the limiting grain size distribution curve has, among other things, a very harmful effect on the cost of production as well as on productivity and on the quality of the product.

#### *1. Soil excavation*

##### *(a) Manual*

This operation makes use of simple manual tools. These are generally the same as those used in agriculture, mining or road construction and include picks, mattocks, spades, shovels, crowbars, rakes, etc. Manual excavation requires a great deal of manpower.

##### *(b) Mechanical*

Various mechanical devices can be used. The mechanical shovel can be variously fitted out to match the work: as a high loader, excavator, grab, or clamshell excavator. A bucket chain excavator is suitable for working an even embankment with a gentle gradient. A bulldozer with blade, an angledozer or a scraper can be used for the horizontal excavation of large volumes of earth. A power cultivator fitted out with a cutter has the advantage of combining excavating and aeration operations and, in addition, rendering the earth highly homogenous. Dual-purpose machines capable of performing the functions of both excavation and elevation significantly increase the productivity of the production process and, to some extent, make scaffolding unnecessary.

#### *2. Screening*

It is frequently necessary to screen the earth to be used in rammed-earth construction. This can be done by removing the largest stones

manually, i.e., those having a diameter greater than 50 mm. Static screens can be used with equal success. These are set up horizontally or obliquely: the mesh size should correspond to the desired grain sizes. As soil suitable for ramming is a powdery material, most vibrating screens are eminently suitable for processing it.

### *3. Pulverization*

If earth is to be rammed, it must be pulverized. This also applies to excessively clayey earth containing hard lumps and to which a sandy fraction must be added. It is advisable to group the pulverizing, grating and mixing operations together. With regard to improving clayey soil with sand, processing the clayey fraction and the sandy component in the pulverizer in alternating fashion will result in a premix of reasonable quality. The mixture goes through the following sequence of further operations: transport, elevation and distribution within the formwork. The pulverizer must be a sturdy machine able to handle stony and sandy soil, and it must be able to project the earth a certain distance in order to ensure good aeration and proper premixing.

### *4. Mixing*

Mixing is advisable when the soil requires homogenization or when it is desirable to add a stabilizer. The most suitable piece of equipment for this operation is a concrete mixer, but a motor cultivator also gives good results in most cases.

### *5. Transport*

This is one of the major problems in rammed-earth technology. Enormous quantities of earth are in fact required in the construction process. The material must be transported horizontally from the borrow to the construction site, and must be transported vertically to the required level as well.

Traditionally, workers who built with rammed earth use manual labour to carry the soil in heavy or light baskets or other receptacles from the borrow to the construction site, the material then being raised by ladder or scaffold to where it is used. The same task can also be carried out in a highly efficient manner by means of hoists. Rendering projectors have been adapted to the same end by a complex process, since the material is not liquid. From a central position the earth can be pumped to anywhere within 40 to 50 m to a height of 100 m.

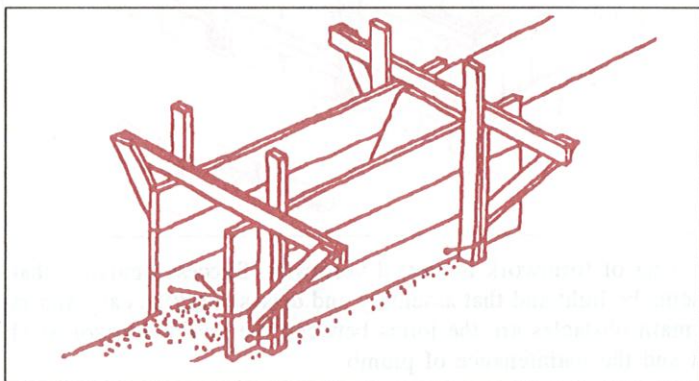
## *B. Formwork*

### *1. Basic types*

Experience shows that formwork is most effective when it is small and simply designed. It must be solid and stable in order to resist the

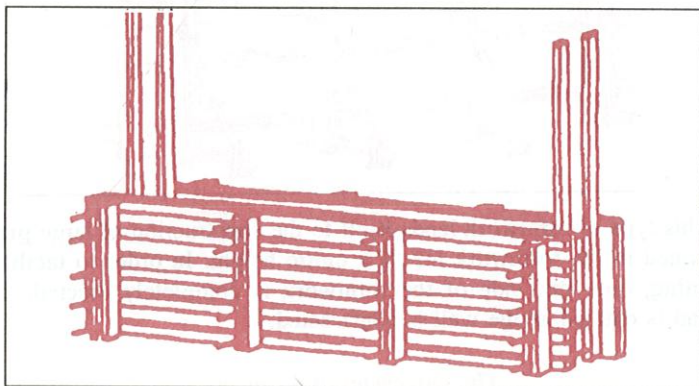
pressure and vibrations resulting from the ramming (a minimum of 300 daN/M<sup>2</sup>). It must be easy to manage, i.e., light and easy to assemble and dismantle - plumb, fit and fastening must be good. Lastly and most importantly, the formwork must be perfectly capable of accommodating changes in height, length and thickness of the walls. A broad range of materials can be used for the formwork such as steel, logs, aluminium, wood and fibre-glass sheets.

(a) *Horizontally sliding formwork*



This system has been traditionally adopted for rammed-earth construction. This type of formwork system was developed by craftspeople and differs widely. It uses fastening systems which follow the principles elaborated above and has the following major advantages: lightness, manoeuvrability of the equipment, and adaptability.

(b) *Vertically sliding formwork*

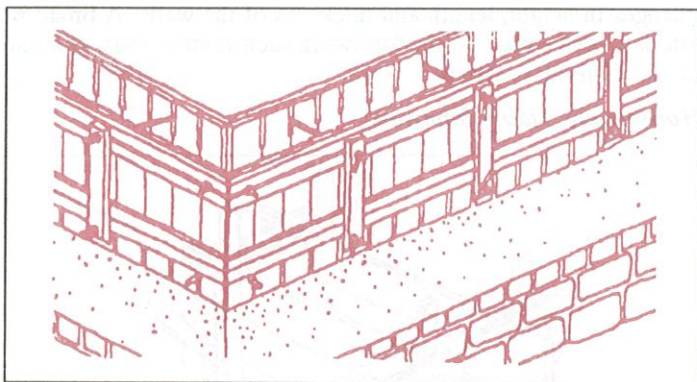


This system is ideally suited to the construction of rammed-earth walls in piers. It facilitates and greatly accelerates the erection of a structure, but the formwork must be carefully designed. The vertical



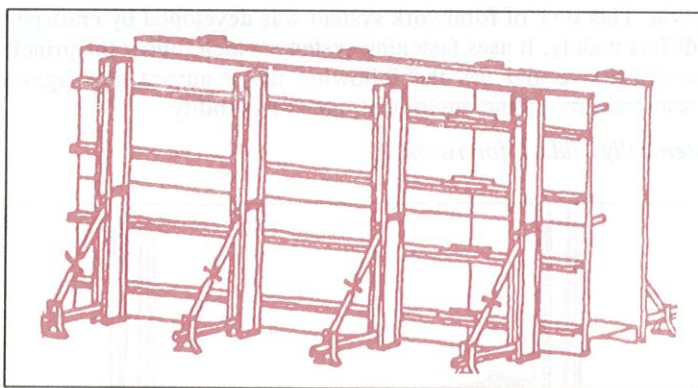
elements holding the formwork in position can be formwork bottoms, construction posts or external frames.

(c) *Integral horizontal formwork*



A ring of formwork is moved vertically. Success demands that the elements be light and that assembly and disassembly be easy and rapid. The main obstacles are the joints between the boards' horizontal alignment and the maintenance of plumb.

(d) *Integral vertical formwork*



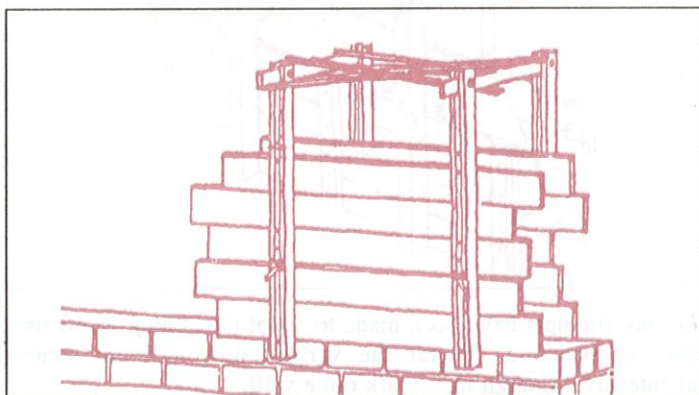
This type of formwork lends itself to the construction of large piers, contained in the formwork for their entire height. In order to facilitate ramming, only one side of the formwork is completely erected. The second is erected as the wall is constructed.

## *2. The movement of formwork*

The moving of formwork poses a serious problem for workers when they are perched at a height of 7 m above the ground on a 40 cm thick rammed-earth wall. The safety of the worker is essential. As a general

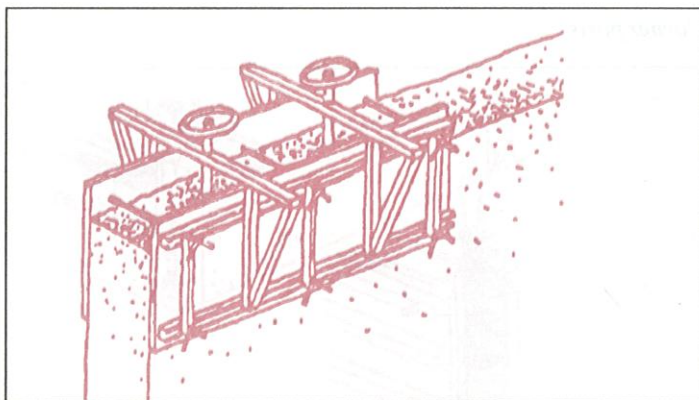
rule, the lightness and manoeuvrability helps to ensure safety. Methods have been developed to avoid the total dismantling and reassembling of the formwork after moving.

(a) *Gantry formwork*



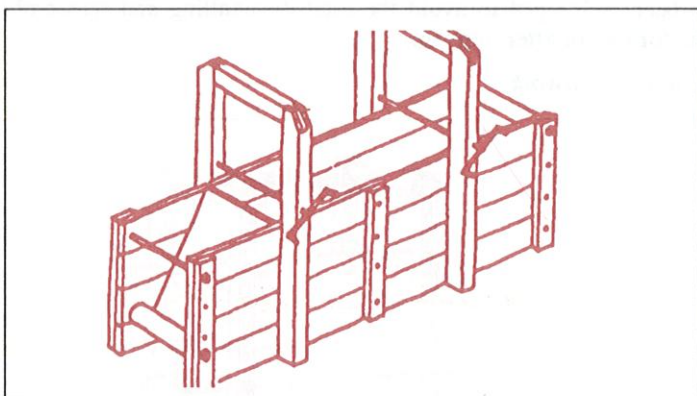
This technique is best suited to the construction of piers or wall sections. The formwork is light, consisting of simple planks, plywood panels or, even, billets which are kept in position by wooden supports driven into the ground and secured at the top. This type of system is used in Chinese rammed-earth construction. Gesamthochschule Kassel (GHSK) (Kassel College of Technology) has reintroduced the technique with a system involving a wooden hinged frame, fastened by threaded rods.

(b) *Formwork with rollers*



The concept of a mobile traveling form, based on the use of rollers, was originated by the Australian, C.F. Middleton, as early as 1952. The system is suitable for the construction of straight walls but requires stationary formwork for bays, corners and partition walls.

(c) *Sliding formwork*

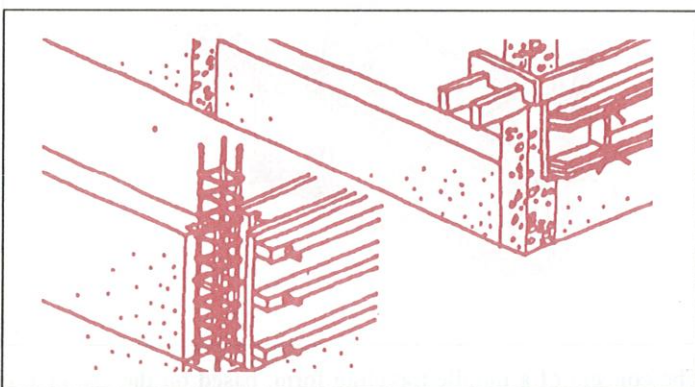


Various attempts have been made to adapt the sliding forms used in concrete construction. So far the various processes are somewhat labour-intensive, though they work quite well.

### 3. *Formwork for corners*

In rammed-earth construction, the building of corners between walls requires the use of special formwork. The play allowed for in the formwork for sections of perpendicular wall can prove to be inadequate if insufficient attention has been paid to corners. These can be fashioned all of a piece or by the alternate, perpendicular overlapping of boards. The provision of chamfered edges reduces the erosion of outside corners. The "T-system" used for bonding partition walls assumes the same principles as those applied to the corners.

(a) *Corner posts*

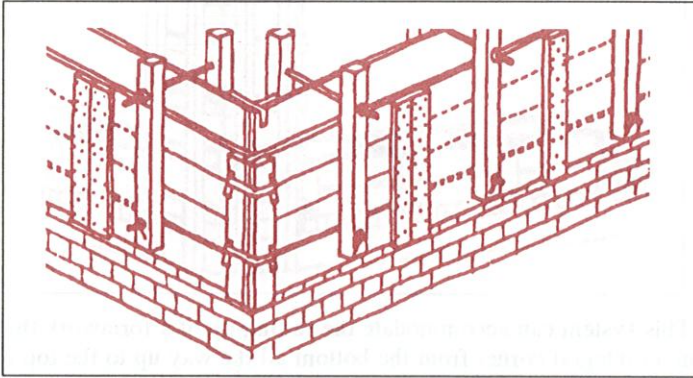


These can be constructed in concrete which can be poured either before or after erection of the rammed-earth walls. Corners can be



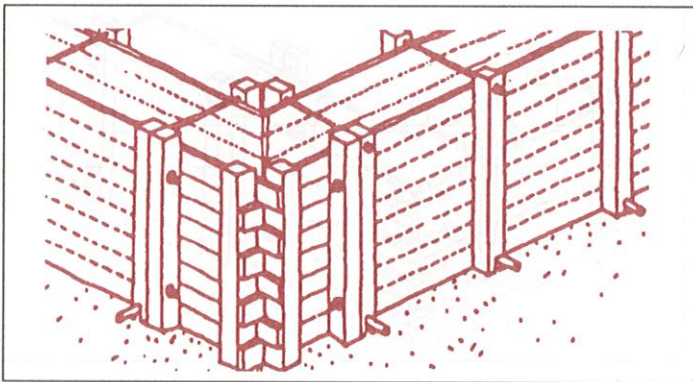
constructed in stone or brick masonry but should be toothed with (conventional) rammed earth.

(b) *Non-modular formwork*



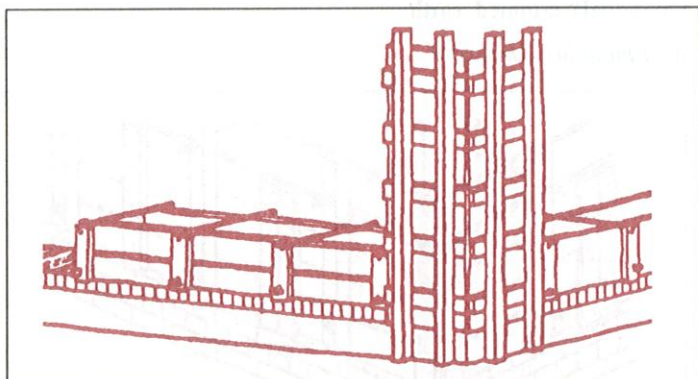
Each corner is constructed using a special element adapted to the particular conditions resulting from the use of non-modular formwork.

(c) *Modular formwork*



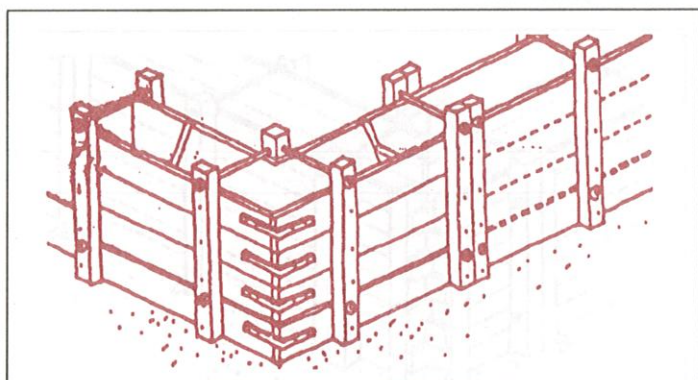
In this system corners are constructed as a single piece, coupling the two inner panels and using a modular formwork on the outside. The design and external dimension must be very precise.

(d) *Integral corner*



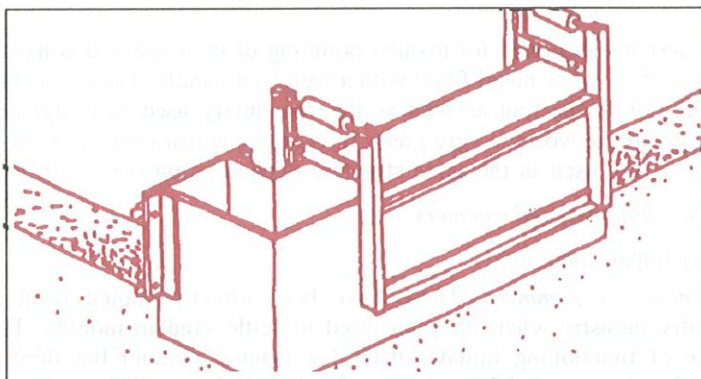
This system can accommodate the setting-up of a formwork that can form an integral corner from the bottom all the way up to the top of the building under construction. In this way it takes care of the very tedious problems of plumb and adjustment.

(e) *Symmetric formwork*



The formwork for both inner and outer faces is modular and symmetric. This system solves the problem of adjusting the panels, but it does not altogether eliminate the risk of a corner separation crack.

(f) *Asymmetric formwork*

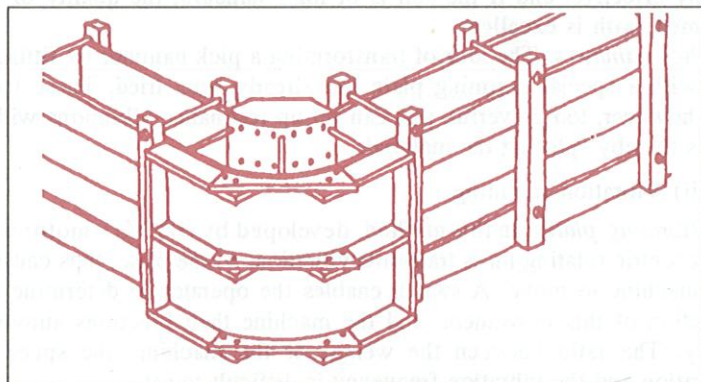


This system is sounder than the completely symmetric corner, given that the forms can be inverted, eliminating the danger of corner separation cracking.

(g) *Variable formwork*

The angle of the corner being formed can be varied by means of systems that incorporate regular or lift-off hinges. These systems are delicate and always pose the problem of gauging the fit of the panels.

(h) *Rounded formwork*



This corner requires special formwork, produced on the site, which can accommodate architectural features. The corresponding operation is very delicate, costly and difficult to carry out.



#### 4. *Rammers*

##### (a) *Conventional rammers*

These are designed for manual ramming of the earth and consist of a mass of wood or metal fitted with a weighted handle. The diversity of the design of the tool as well as the vocabulary used to designate it throughout the world is very great. In certain countries several kinds of rammers are used in the same structure depending on the job in hand.

##### (b) *Machine-assisted rammers*

###### (i) *Impact ramming*

*Pneumatic rammers:* These have been directly copied from the foundry industry where they are used to settle sand in moulds. Their mode of functioning imitates that of a manual rammer but they are capable of a much higher impact frequency (up to 700 strokes per minute). Of all the pneumatic rammers available, only the "soil" rammers are effective, of which there are numerous commercial types. Pneumatic rammers must be neither too heavy (15 kg maximum) nor too powerful. If they are, they will destabilize the formwork and cause the rammed earth to bulge, or they will penetrate the earth. They should have a long stroke approximately 20 cm) and run on regulated air. They should be able to attain a pressure of 5 daN/cm<sup>2</sup> and barely beyond that. Compressors are very expensive, costing about \$5000. Notwithstanding the expense, however, ramming carried out by a pneumatic rammer is highly effective, and if the soil is of high standard, the quality of the rammed earth is excellent.

*Pick hammers:* The idea of transforming a pick hammer by fitting it out with a special ramming plate has already been tried. These tools are, however, too powerful, and can set up resonance vibrations within walls thereby splitting the material.

###### (ii) *Vibration ramming*

*Vibrating plates:* In this method, developed by GHSK, a motor with an eccentric rotating mass transmits vibrations to the plate, thus causing the machine to move. A switch enables the operator to determine the direction of this movement, and the machine then functions automatically. The ratio between the weight of the machine, the speed of operation and the vibration frequency is difficult to set.

*Vibrating rammers:* Versions of these machines powered by combustion engines or electric motors are available on the market. They are heavy, cumbersome and expensive. Their use has been the object of numerous tests with very modest results and builders are advised against using them.

## II. PRODUCTION OF ADOBE BLOCKS

### *A. Preparation of the soil*

Soil suited to making adobes has a rather clayey or very silty texture and is quite cohesive. This cohesiveness makes excavating the earth, whether dry or wet, a difficult task. The excavation sites are often waterlogged and muddy. The traditional method of preparing the earth is thus labour-intensive and is done by foot. The soil must be prepared with great care in order to ensure a high standard of adobe. There are other methods of preparation, some of which are mechanized. A third category, lying between the first two, utilizes draught animals.

#### *1. Chopping of fibres*

Plant fibres, generally straw, are frequently added to the soil. The stalks are cut using sharp-edged tools. However, manual and power straw choppers, capable of cutting large quantities of straw and other fibres into length of between 1 and 30 cm, are commercially available. The normal price of such choppers starts at \$1000 for the manual type and \$1500 for motor-driven ones. Fibre choppers can also be used to prepare plant cuttings.

#### *2. Pugging*

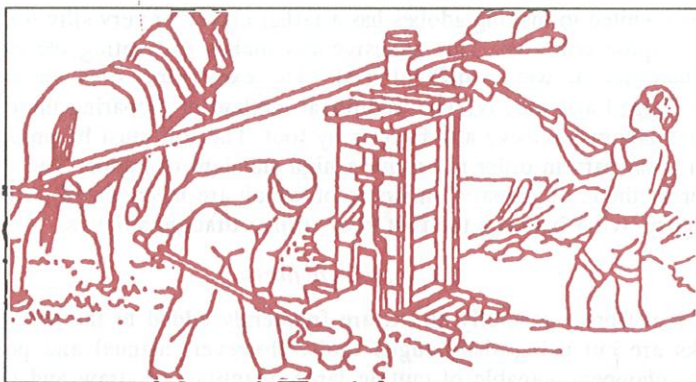
The preparation of the earth entails a long pugging operation. In many regions, animals that go round in a circle over a specified area, perform this work by treading the earth with their hooves. Animals that can be used for this purpose include donkeys, mules, oxen and horses.

The material can be pugged in a pit with mechanized plant such as shovel excavators and tractors that can combine the operations of excavation, mixing and transport. The pit should have a stable bottom and an inclination so that the machine can get out. The manoeuvring space for the machine must be sufficiently large. The quantities mixed are enormous, being of the order of  $10 \text{ m}^3/\text{h}$ .

Pugging can also be carried out in pug mills. These can be set up in a smallish drum and driven by a motor or else hauled by animals over a given area - two weighted truck wheels will serve the purpose. Wheel tracks should not be left in soil and this can be avoided by devising a system that throws the soil back under the wheels so that it is constantly remilled. An improvised pugging set-up costs only a few dollars while a mill in a containment vessel costs something of the order of \$2000. Such plant is very heavy and a typical output is in the neighbourhood of  $7 \text{ m}^3$  per day.

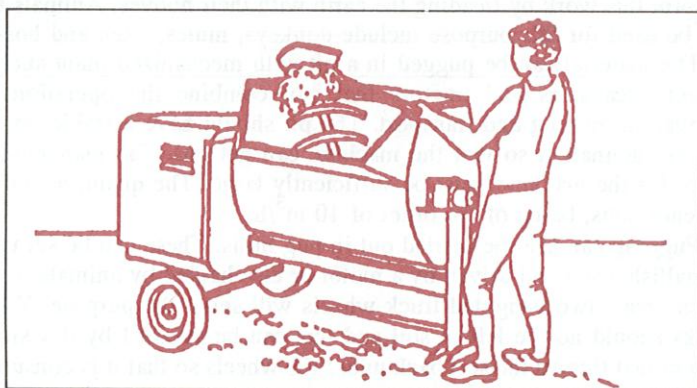
### 3. Mixing

#### (a) Vertical mixers



The most common of these can be made using very basic materials; a few planks and timbers, ropes, steel wire etc. They can be operated by animals. The lever should be at least 2.5 m long, and the animal should not work more than five hours per day. Mechanical vertical mixers exist as well. They must be solidly built and the standard output is  $10 \text{ m}^3$  per day.

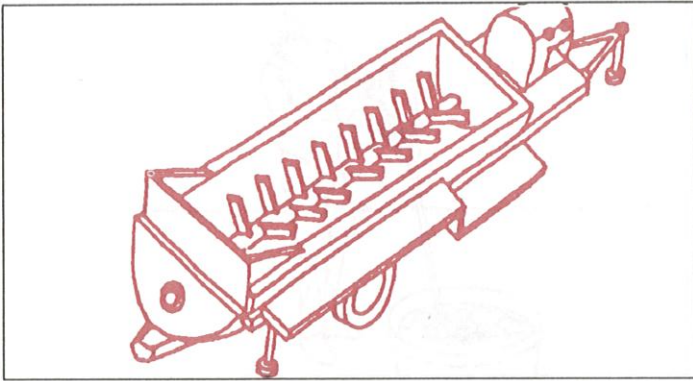
#### (b) Rendering mixers



As these are very sturdy, these mixers should really be used with liquid soil rather than plastic soil. They are capable of a daily output of approximately  $8 \text{ m}^3$ .

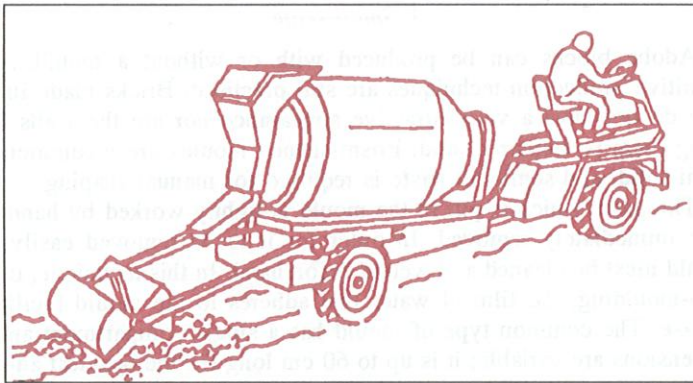


(c) *Linear mixers*



These are widely used in production units capable of medium and high output. There are a number of variations on them. For example, they can have a single or double shaft; they can be of the constant or discontinuous-flow type; they can be of heavy or light construction. Their output is very high and muddy earth can be dumped into a pit allotted for the purpose. The smaller linear mixers are capable of outputs of between 4 to 5 m<sup>3</sup> per day. The bigger mixers, which have been adopted from the ceramics industry, have an output of 50 m<sup>3</sup> per day.

(d) *Concrete mixers*



Although poorly rated, standard tilted-drum concrete mixers are capable of doing the job. Their output is low and the resulting mixture often lacks homogeneity and suffers from lumpiness. Their main advantage is the wide range of models available, ranging from small to large, suitable for connection to a tractor PTO (power take-off), mixer trucks, and special wheeled plant.

(e) *Screw mixers*



It is also possible to work with small quantities using drums provided with a screw of the sort used for paint and plaster. In this way it is possible to prepare 50 litres of mixture in 10 minutes by making successive batches.

(f) *Planet wheel mixers*

These are ideally suited to preparing mud even when it must be mixed with plant fibres. The smallest ones have a batch capacity of 100 litres, and an output of 10 m<sup>3</sup> per day.

*B. Manual production*

*1. Small-scale*

Adobe blocks can be produced with or without a mould. Very primitive production techniques are still practised. Bricks made in this way do not have a very attractive appearance nor are the walls built using them particularly solid. Prism-shaped moulds are recommended. Semi-solid, and semi-soft paste is required for manual shaping.

The paste which is put in the mould is lightly worked by hand and then immediately removed. In order for it to be removed easily, the mould must be cleaned and wetted beforehand. In this technique, called slop-moulding, the film of water that adheres to the mould facilitates release. The common type of mould has a single compartment and its dimensions are variable; it is up to 60 cm long for the heaviest adobes. It can also have multiple compartments and be capable of moulding up to four adobes at a time. These moulds are made of wood or iron, some even being made of plastic. The bricks undergo considerable shrinkage and their quality must be carefully monitored.

To produce better quality, denser and more resistant bricks, it is advisable to work with a semi-firm paste. The mould must be very clean, and then it is dipped into water and the inside sprinkled with sand. Using this technique, known as sand-moulding, a given quantity of

earth is shaped roughly into the form of a ball, rolled in the sand and then thrown with force into a single-compartment mould. The ball is made firm with the fists, care being taken not to neglect the corners. The excess is removed with a wooden guide strip. To facilitate release, only the earth coated with sand should adhere to the sides of the mould. There are many different types of moulds, some having bottoms and some not. The adobes are turned out of the mould on to the drying area. This technique means that the earth has to be stored near the moulding area and several moulds should be available. It is advisable to work standing at a table. There are even tables with built-in moulds and ejection levels. The adobe should be carried to the drying area on a small board (the bottom of a mould). The output using the moulding technique is of the order of 500 adobe blocks per day.

## *2. Large-scale*

Large-scale production requires modifications to the techniques of small-scale output as indicated in the following.

### *(a) Multiple moulds*

These can be a ladder-like array in which moulds are juxtaposed or alternatively large parallel piped moulds can be used. In this way 10-25 adobes can be produced at once. The earth should fill the entire mould. It must, therefore, be more liquid, in the soft-paste state. Apart from this change in moisture content, the previous preparation remains the same. The earth is then poured into the moulds by means of a wheelbarrow, dumper, frontloader, or even straight from the mixer which, in this case, is self-propelled, towed, or mounted on a truck. The soil is then levelled with a kind of scraper so that it is evenly distributed within the mould, including the corners. Some time may be allowed to elapse before removal from the mould, but usually this is done immediately after the previous step. The whole operation is then repeated without interruption. Large moulds must be cleaned properly either by allowing them to soak in water or spraying with a powerful jet of water. The cleanliness of the moulds and the moulding stage are crucial to ensuring the quality of the adobe. Owing to considerations of weight, the moulds should be made of wood or plastic as opposed to steel. They should be easy to manipulate by no more than two persons. Wood should be treated against rot and warping. The outputs possible with this moulding technique, with a crew of five or six workers, ranges from 8000 to 10,000 adobe blocks per day.

### *(b) Sawn adobe blocks*

It is possible to make a single very large adobe ( $4 \text{ m}^2$  for example) with a mould consisting of four two-metre long planks. A soft paste is used. The resulting adobe slab is then cut into several small adobes with a taut wire saw on a wooden support or else using a plank with a studded



edge. The output using this technique is similar to that of the above technique, and only a very modest investment is required, although the finish obtained is not so good. The moulding area must be absolutely flat.

### *C. Mechanized production*

The difference between large-scale production using multiple and mechanization processes is not all that great. The basic techniques are as follows.

#### *1. The moulding box*

A metallic mould containing a large number of compartments is mounted on a frame on wheels. The mould is lifted by means of a lever arrangement after it is filled. The adobes are deposited on the ground. The wheeled mould is then pulled to the next moulding point. The moulding cart should be capable of being cleaned each time. A mobile hopper can be added and positioned above the mould for filling by a dumper. Soft paste is poured into the mould from the hopper which is drawn over the mould. The excess earth is removed with a scraper which can be fitted to the hopper. The standard output of such a system is of the order of 7000 to 10,000 blocks per day, and it has been refined with the development of the Hans Sumpf moulding box in the United States which was designed as an independent unit. This machine can achieve an output of 20,000 blocks a day. The adobes are deposited on to impermeable paper which is unrolled directly on to the ground over a wide production area. The adoption of a machine of this sort means that the entire upstream production plant must be modified to cope with the enormous increase in capacity.

#### *2. The cutter disc box*

Cutting by means of a wire can be automated and the wire replaced with cutter discs. A hopper fitted with a barrel lays down a continuous sheet of soft paste which is cut into thin strips. The machine is stopped at a fixed distance from its starting point and the thin strips are cut transversally by another set of cutter discs. The output is very high, amounting to 15,000 blocks a day, and the investment is low. The production surface must be very flat and clean and the mixture highly homogenous and of an ideal consistency. The user of this system must, therefore, be absolutely sure of what he is doing. To date only prototypes are known, but these appear to be most promising.

#### *3. Extruders*

The extrusion of adobes opens several very attractive possibilities. Applied to the manufacture of adobes, extrusion can serve as the basis of three principal processes.

*Vertical extruder:* This consists of a vertical mixer provided with an extrusion nozzle. The system can be motorized or it can be driven by a draught animal. The process, although giving good results, is hardly used nowadays. With a small mixer weighing about 500 kg, output can reach 1500 bricks per day.

*Horizontal extruder:* Adapted from the ceramics industry, this machine was widely used in the United States in the 1940s. It is still standard in India. Although it involves a heavy financial outlay, the system is efficient. It is capable of the same production rates as achieved in the brick industry for equivalent products. Nevertheless, the soil used for making adobes is sandier than that used for making burnt bricks. Consequently it is more abrasive, and a significant degree of wear, resulting from friction, must be allowed for.

*Mobile extruder:* Mobile extrusion units mounted on a frame on wheels are commercially available. These are heavy pieces of equipment weighing approximately 30 tons and combine a mixer, a generating unit and an extruder. Some units are already operational in various parts of the world for the production of burnt bricks. They could also be adapted to the production of sun-dried bricks. The system has an output of between 2500 and 3000 bricks per hour.

#### 4. Press

The traditional moulding table can be replaced by a press. The moisture content of the soil is not the same: and soil is either a semi-solid or solid paste. The required pressure does not exceed  $20 \text{ daN/cm}^2$ . One or more holes, 10 mm in diameter, are bored into the cover so as to facilitate the extrusion of any excess. Sometimes a small board is inserted into the mould and the earth ejected on to this for transporting. Output is much higher than it is for compressed blocks.

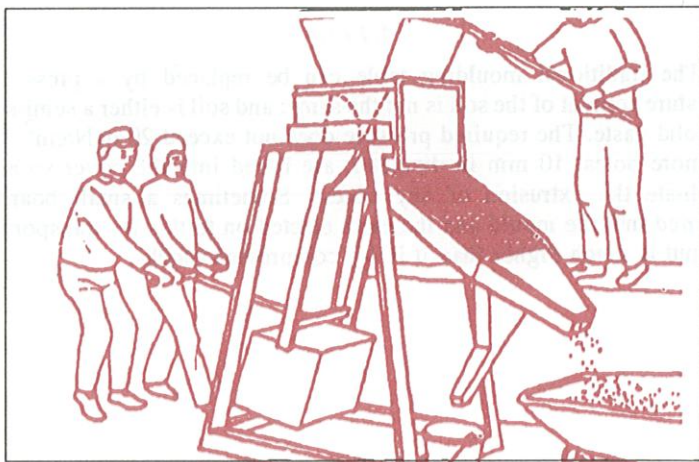
### III. PRODUCTION OF COMPRESSED BLOCKS

#### A. Pulverization

In order to obtain uniform mixing of the mineral components, water and stabilizer, lumps of more than 200 mm in diameter after excavation must be broken up. Grains with a homogenous structure, such as gravel and stones, must be left intact, and those having a composite structure (clay binder) broken up so that at least 50 per cent of the grains are less than 5 mm in diameter. The soil must be dry. Wet soil can only be handled by certain mechanized systems. Two basic approaches are used, grinding and pulverization.

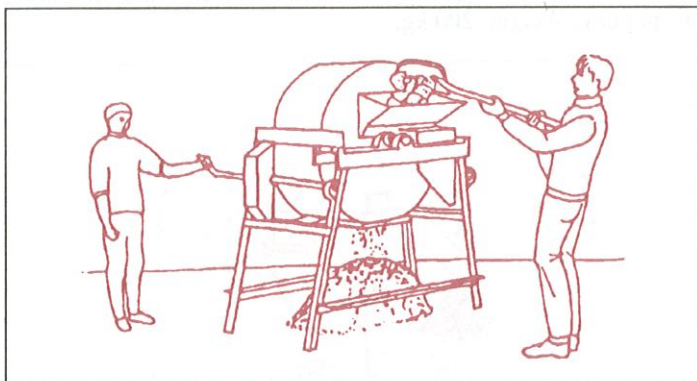
(a) *Grinding* followed by screening. The material is pressed between two surfaces - a rather inefficient and tedious process in which useful stones are broken up. Only simple machinery is required;

(b) *Pulverization*: The material is hit with great force and disintegrates. The machinery required is complex but performs satisfactorily. At the delivery end, any large pieces left can be removed by means of a screen. The following are some of the techniques used for pulverization:

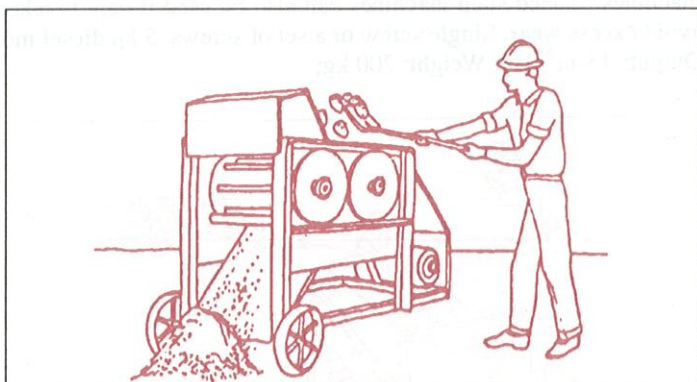




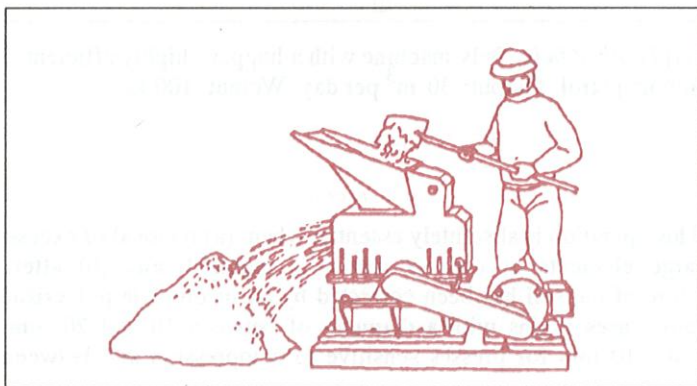
(i) *Pounding*: Manual process; very slow;  $1 \text{ m}^3$  per day per man; screening absolutely essential;



(ii) *Carr*: Four series of rods turning at 150 rpm. Manual or motorized (electric) version, 1.5 W motor. Excellent mechanical efficiency, up to  $10 \text{ m}^3/\text{day}$ . Weight: 260 kg;



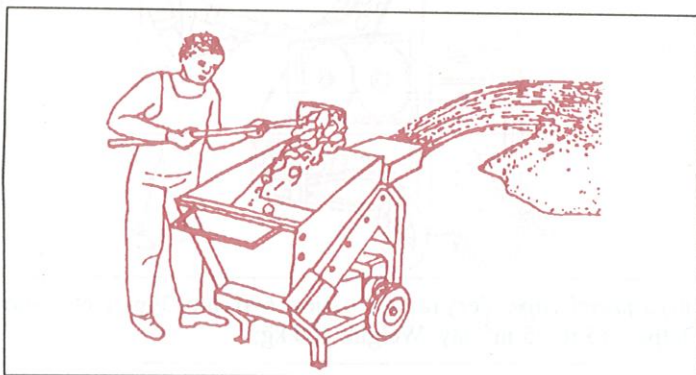
(iii) *Squirrel cage*: Very rapid rotation: 600 rpm, 3hp electric motor. Output: 15 to  $25 \text{ m}^3/\text{day}$ . Weight: 150 kg;



(iv) *Hammers*: Several spring-mounted hammers on a central axle beat the earth at a high frequency. 10 hp electric motor. Output: 40 m<sup>3</sup> per day. Weight: 200 kg;



(v) *Screw*: The same system as used in conventional composting machines. Indeed such machines can also be used if care is taken to avoid excess wear. Single screw or a set of screws. 5 hp diesel motor. Output: 15 m<sup>3</sup>/day. Weight: 200 kg;



(vi) *Toothed belt*: Only machine with a hopper - highly efficient. 3 hp motor: petrol. Output: 30 m<sup>3</sup> per day. Weight: 100 kg.

## B. Screening and mixing

### 1. Screening

This operation is absolutely essential when: (a) removal of excessively large elements or organic matter is required; and (b) after the structure of the soil has been corrected by an incomplete pulverization. In most cases grains with a diameter of between 10 and 20 mm are passed - 10 mm for presses sensitive to compression and between 20

and 25 mm for those less sensitive to compression (hyper-compression). There are four basic methods of screening.

(a) *Fixed screen*

Set up either obliquely or suspended. The operation is manual and easy to carry out. There are two basic operations. Raw soil is thrown with a shovel against the sieve. The sieved soil is loaded into a wheelbarrow, unsieved material is rejected, or set aside for other use. Low yield: 1 m<sup>3</sup> per hour per worker.

(b) *The alternating screen*

The simplest process consists of placing a frame sieve, on a pipe and a wheelbarrow. The sieve can also be suspended from a branch and set moving back and forth. A special manual tool has been designed along these lines consisting of a few planks, a cut-away barrel and chicken wire. The output obtained using the stationary sifting system is 2 m<sup>3</sup>/hour per worker.

(c) *Rotary screen*

A cylinder made of wire netting or metal is rotated either manually or mechanically. Its construction is very simple. It is possible to pass the soil through a number of stages series and so separate into several fractions. Agricultural rotating sieves such as peanut sieves are suitable for the operation. Mechanical rotating sieves of all sizes ranging from 1 to 30 HP are commercially available. Theoretically these sieves are capable of an output as high as 14 m<sup>3</sup>/hour.

(d) *Vibrating screen*

Either a single vibrating screen or a combination of several screens, usually superimposed, can be used in this process. This system offers the same advantage as the rotating sifter in that it makes it possible to separate the soil into several fractions, permitting its reconstitution. They are used in excavations and quarries. Vibrating screens of average size have outputs in the region of 5 m<sup>3</sup> per hour.

## 2. *Mixing*

This is a particularly important stage. A uniform mixture is essential, regardless of whether a stabilizer is used or not. Where manual labour is relied upon, the heap of soil must be turned over at least four times. When a powerful mechanical mixer is available three or four minutes



in the mixer is enough. It is important to mix the material dry first. Water should be added to the soil either with a sprinkler, or a mist sprayer, or by means of pressurized steam. Mixing can be done as described below.

(a) *Manual mixing*

This can be done by means of a shovel, hoe, rake or any other simple tool; output: 1 - 2 m<sup>3</sup> per day per worker.

(b) *Manual mixer*

Various systems have been devised which make use of a 200-litre oil barrel. The Tallahassee School of Architecture is in the forefront of the development of such systems. Their output, at 1.5-2.5 m<sup>3</sup> per day per worker, is slightly higher than that achieved using a shovel.

(c) *The motorized mixer*

A motor can facilitate mixing, as this is a slow operation. Conventional concrete mixers are not recommended because of the formation of lumps and crumbs in the soil.

(d) *Mixer with blades*

The motor cultivator is suitable for simultaneously crushing and mixing. The range of such machines available on the market is very broad with respect to size and power. Output is upwards of 4 m<sup>3</sup>/day.

(e) *The planet wheel mixer*

This is the conventional mixer used for concrete extrusion. Small mixers are difficult to find. A 0.5-HP electric motor or a 0.75- HP diesel motor is required to process 10 litres of soil. A 180- litre planet wheel mixer has an output of 15 m<sup>3</sup> per day.

(f) *The paddle mixer*

This is similar to a rendering mixer but sturdier. It works well with very dry soil but can break down if the soil is wet (12-15 per cent moisture content). Required power for electric motors is 0.75 HP per 10 l, and for diesel engines, 1 HP per 10 l. Output for a capacity of 150 l installation is 8 to 10 m<sup>3</sup>/day.

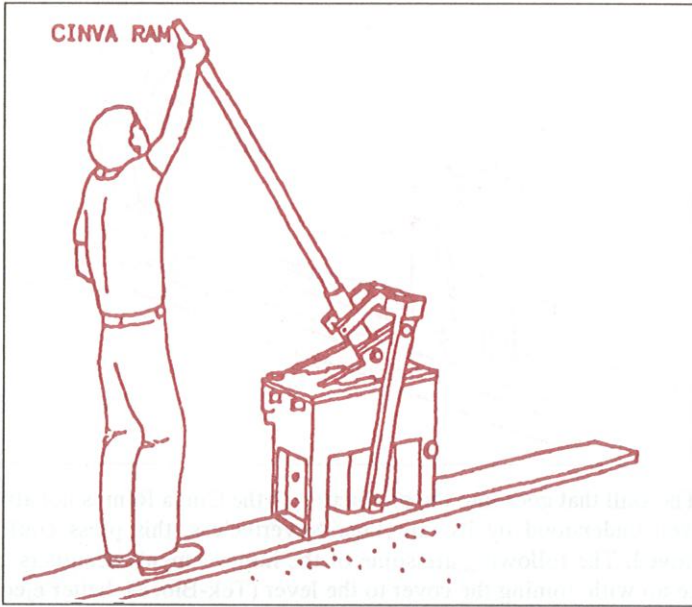
(g) *Linear mixer*

A discontinuous helical screw shaft is fitted with either single or double blades. The shaft must be very sturdy. Extremely heavy and expensive, this type of plant is rarely used.

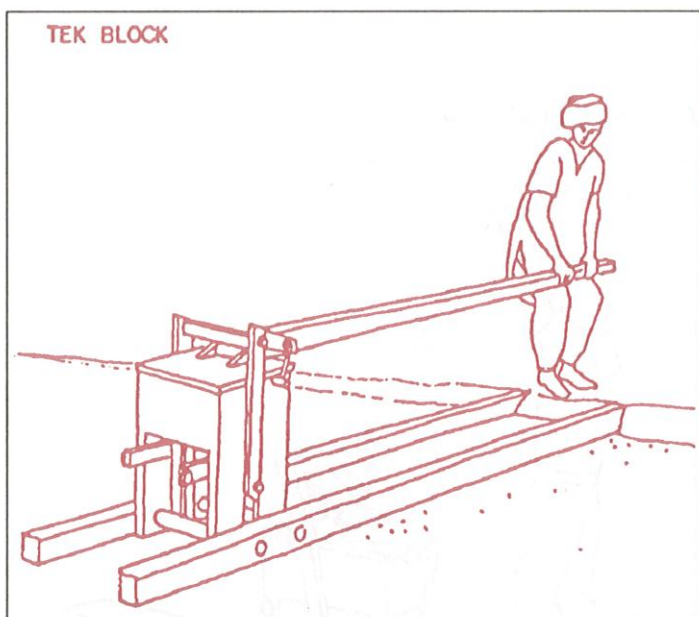
## C. Types of presses

### 1. Manual presses

#### (a) Light mechanical presses



The advantages of Cinva Ram type presses are that they are light, sturdy, low-cost, and simple to produce and repair. Their main disadvantages are: they wear out prematurely (coupling rings), have only a single moulding module, can exert only low pressure and have a low output. Nevertheless, they are one of the best presses of their type on the market, and it is usually the copies which wear out prematurely.



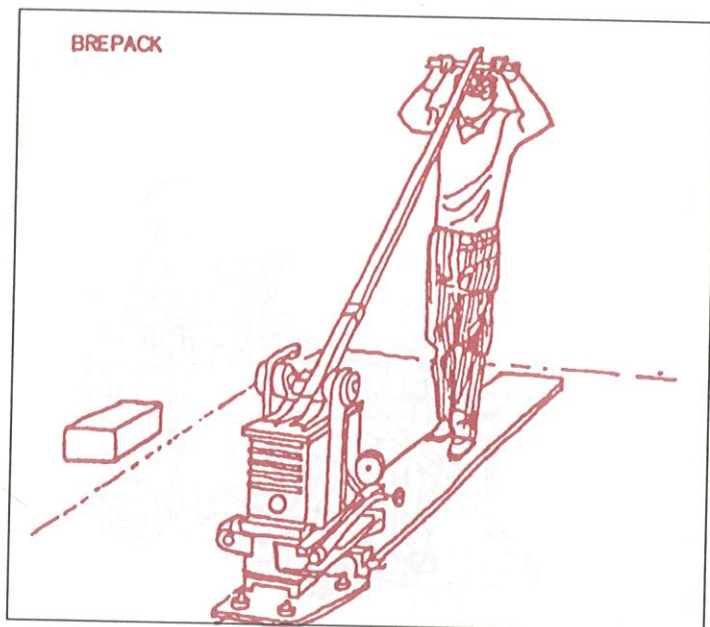
The skill that goes into the production of the Cinva Ram is not always so well understood by its imitators. Nevertheless, this press could be improved. The following are some of the improvements designers have come up with: joining the cover to the lever (Tek-Block); better ejection (Stevin, Ceneema), greater moulding depth (Ait Ourer); better transmission of energy (Dart-Ram); fold-down cover (Meili); standard steel profile (Unata); dual compaction action (C + B1); compartmentalized mould (MRC 1); and production of perforated blocks (Ceta-ram). These technical improvements also aim at refining the production process which, in the last analysis, is relatively independent of the mechanical cycle of the press.

Production is in fact determined to a greater extent by the mode of organization of the work, the mode of payment of the crew and the prevailing working traditions. So it is that the average output of a Cinva Ram or similar press is 300 blocks/day although this could be increased to 1200 blocks/day.

These presses are produced in a number of countries including Belgium, Burkina Faso, Cameroon, Colombia, France, Morocco, New Zealand, Switzerland, United Republic of Tanzania, United States of America and Zambia, among others.

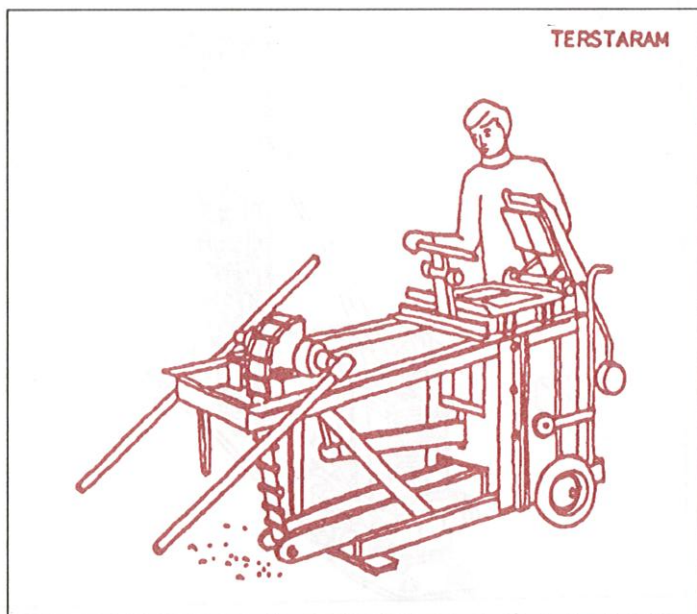


(b) *Light hydraulic presses*



A small press, the Brepak, makes a major improvement to the Cinva Ram. The swivel and rod system of the Cinva Ram is replaced with a hydraulic piston which enables it to achieve pressures of  $100 \text{ daN/cm}^2$ . The resulting blocks have identical dimensions to those made using the Cinva Ram but are approximately 20 per cent denser. The hyper-compression means that it is suitable for compacting highly expansive soils such as black cotton soils.

(c) *Heavy mechanical presses*



These can produce pressures greater than the minimum threshold of  $20 \text{ daN/cm}^2$ . These presses being sturdy, do not wear out easily. The presses are easy to manipulate and maintain. They have interchangeable moulds. The fold-down cover of these machines allows precompaction. The back and forth motion from one side of the press to the other is eliminated. The design of the machine permits better organization of the work that is carried out around the press.

## 2. Motorized presses

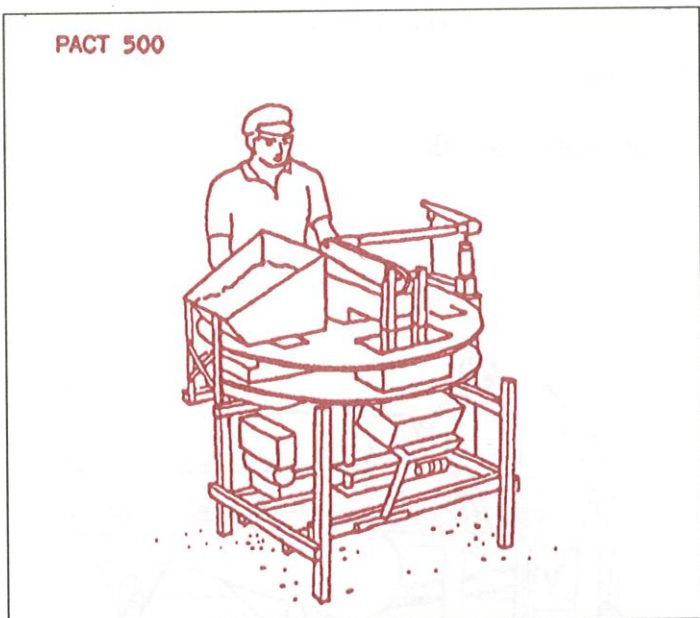
### (a) Mechanical presses



These represent a new generation of presses which are currently available on the market and which appear destined for a bright future. Despite their cost, which is of the order of four to seven times that of heavy manual presses, their economic viability is excellent. Some of these presses, such as the Semi-Terstamatic, are direct descendants of the heavy manual presses and have benefited from the lessons learned on the older type. The Semi-Terstamatic was at one time on the market under the tradenames Major and LP9 (Landcrete).

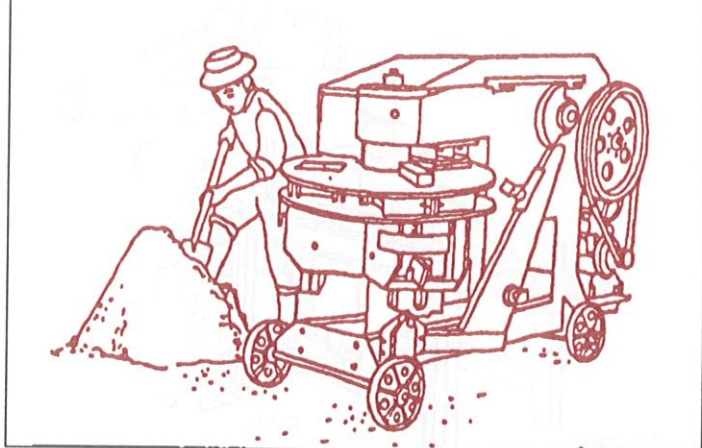


### PACT 500



Motorized mechanical presses belong to one of two groups: those having a fixed table and single mould, simple and sturdy; and those having a rotating plate and multiple mould (three or four), which under certain conditions raises the production rate. In the first case, the mould can be changed rapidly and cheaply, whereas with a rotating plate changing the mould takes more time and is costlier. The tables can be turned by hand (Pact 500) - a tiresome operation - or mechanically. The latter system requires more sophisticated mechanism and more energy.

## CERAMATIC

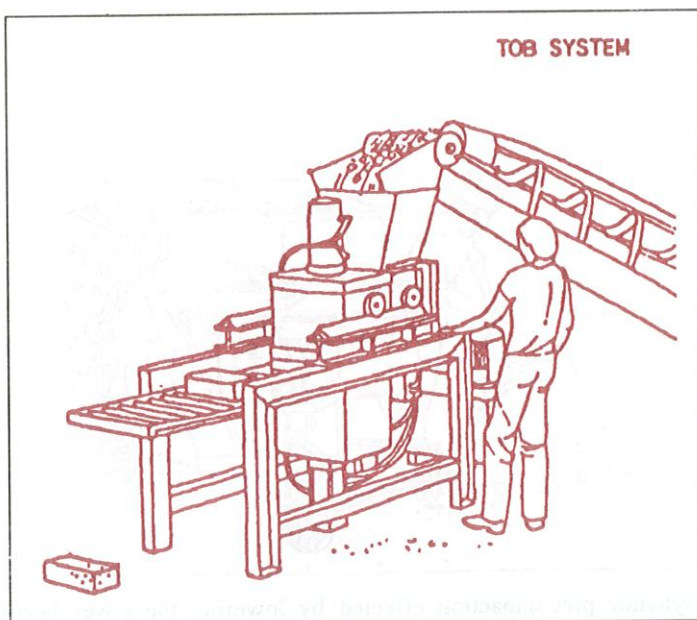


Dynamic precompaction effected by lowering the cover becomes possible with the systems using a single mould and this confers significant advantages. By adjusting the tapered precompacting roller located between the feeding position and the compacting position, precompaction with rotating table presses becomes possible. The level of the earth should be slightly above the sides of the mould and this is only possible when the press has a feed hopper.

The designers of this type of press have encountered major problems which were still not resolved when the presses were brought to market: the soil disturbs the functioning of the machine by getting into sensitive areas; the safe operation of the machine must be ensured, lest it be damaged; the press must not be allowed to operate in reverse, which would happen if the electric motor were installed backwards; where the available pressure is less than the required pressure (when there is too much earth in the mould, for example), the press will block (the removal of a half-compacted brick would slow production). Accordingly, the press ought to be provided with a compensating spring and a motor-release system.

Finally, these presses should be designed to give the user the choice of an electric motor, a combustion engine or another type of motor. These presses are very largely dependent on the upstream production operations of screening, proportioning and mixing.

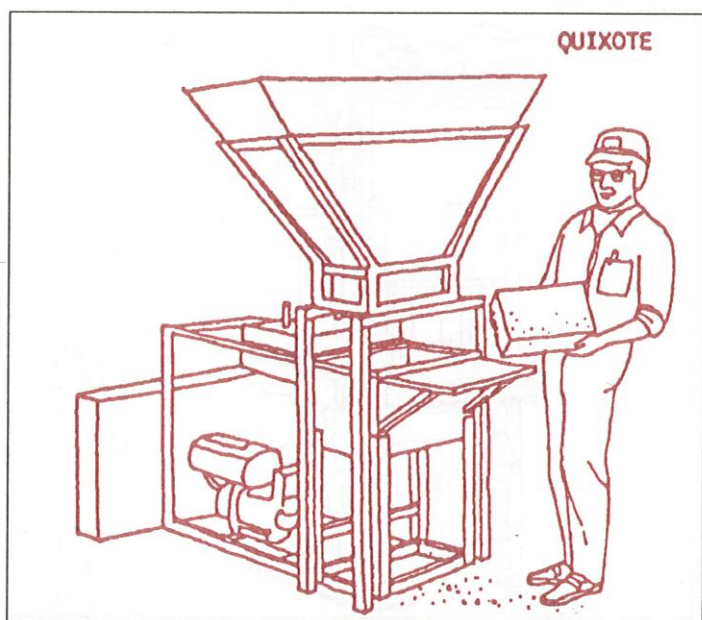
(b) *Hydraulic presses*



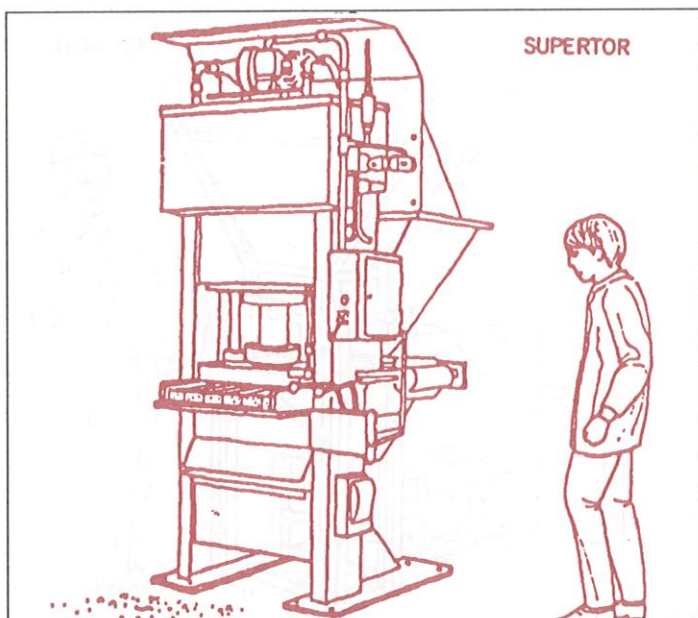
These are stand-alone presses capable of medium output. Hydraulic presses had a certain vogue in the 1950s but rapidly disappeared from the market. New presses of the same type were launched in the 1970s, but their reliability is disputed and they have brought as much disappointment as satisfaction. Nevertheless, hydraulic systems have the advantage, owing to the functioning of the piston and their compactness, of permitting a long stroke. It follows that compression ratios equal to, or greater than, 2 can be achieved.

These systems can be easily adjusted to match the composition of the soil. They can also be provided with a hopper - the first step towards automation. Furthermore double compaction can easily be carried out with a hydraulic press.





It is also true, however, that the hydraulic press gives rise to several problems all of its own, such as a delicate hydraulic pump. Apart from this, if the rotating plate is hydraulically driven as well, the oil reservoir should have a volume of at least 200 l. Despite such a large quantity of oil, the temperature of the fluid can quickly rise above 70°C in tropical climates. This is the maximum permissible temperature, if all the hydraulic components are to function properly. Apart from those that can tolerate a temperature of 120°C, but which are difficult to replace if they break down. The alternative is an oil-cooling system which makes plant complex. The oil must be changed but it may not always be available.



These presses may function well in the right circumstances, for example, a technologically advanced environment but they often perform poorly in rural surroundings or even on the outskirts of cities in developing countries.

Many models of this type of press have been built and the market sees the steady appearance and disappearance of models. Rarely have they been known to be reliable.

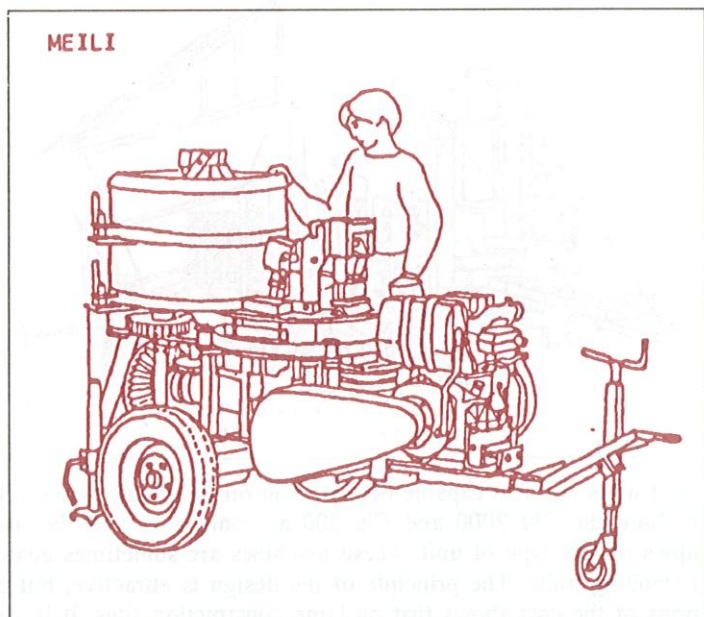
#### *(c) Mobile production units*

Power presses often necessitate a major mechanization of the upstream process. Accordingly, designers' research has proceeded along the lines of integrating all the plant equipment used in self-contained production units, which reflect current production trends. However, although the cost can be reasonable, the economic viability of self-contained production units continues to pose a problem. They do not all operate in the same way and all conditions must be optimum. Even in the industrialized countries, these machines operate in very tight economic conditions. In developing countries they are often uneconomic. There are two types of mobile production units.

##### *(i) Light units*

These offer the advantage of opening up a totally new market in industrialized countries and in the urban areas of developing countries, namely leasing to do-it-yourself builders. Indeed these machines can be rented for the entire block production period at a relatively low price. Even so this type of machine still suffers from a few defects, mainly

because of a lack of integration between the different types of equipment that have been brought together. An effort should be made to harmonize the outputs and cost of these machines with the different stages of production they integrate.



The light units can operate in mechanical presses. At present, the Meili unit, which is manufactured in Switzerland, is the only example on the market of this type of press. There is not a very wide range of this class of unit and so far there is no totally integrated unit on the market. The pulverizer still suffer from defects.



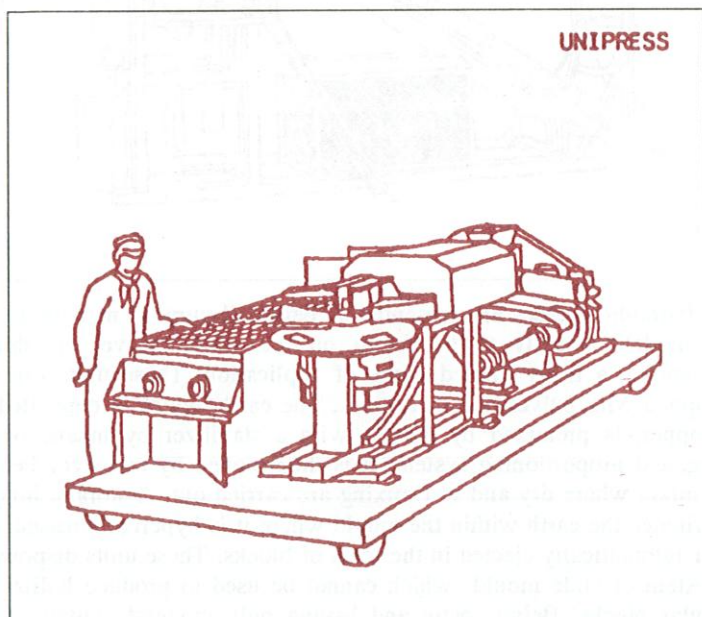
## EARTH RAM



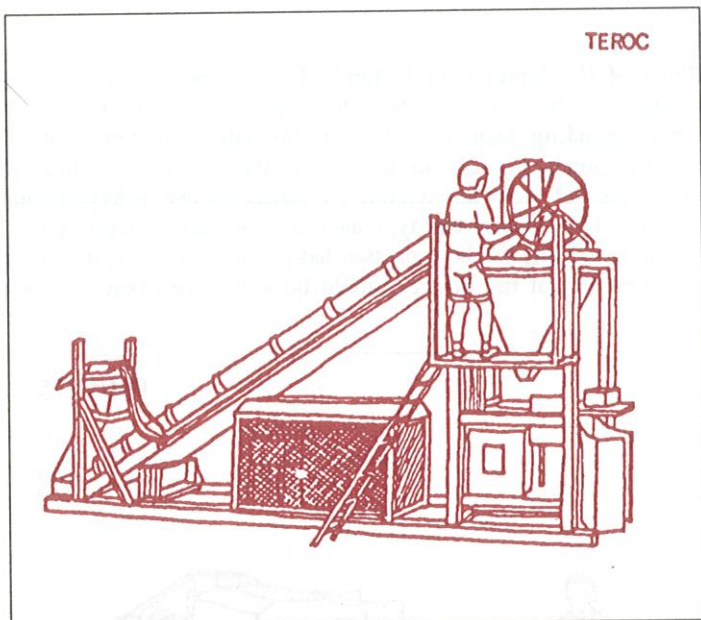
Light units are also capable of operating on hydraulic presses. The Earth Ram, the Clu 2000 and Clu 300 are only a few of the many examples of this type of unit. These machines are sometimes adapted from standing units. The principle of the design is attractive, but calculations of the cost shows that on large construction sites, it is more economic to purchase the production materials (pulverizer, mixer, press) separately. Unintegrated plant is not less efficient and it is not clear that integrated equipment is more convenient.

## (ii) Heavy units

Some of the larger manufacturers have proposed entirely mobile units which can be taken anywhere, but which are very large and heavy. The corresponding annual production capacities are very high. The plant corresponds broadly to those described in the previous paragraph. At present, there is a tendency towards the use of hypercompression. Only a few units of this type have been manufactured to date. The economic feasibility of these presses has yet to be demonstrated, and a thorough survey of the market should be undertaken before acquiring them.



At present, only a single unit operating on mechanical presses is known. Its design is based on the concept of a combination of existing units all mounted on a single chassis and goes by the name of "Unipress". This plant is ordinarily used for the production of burnt bricks. Attempts in Egypt to adapt it to compressed blocks have met with some major but not at all insurmountable obstacles. The plant is very sturdy.



Hydraulic presses are presented as being all-purpose machines, but the models actually to be found on the market have, all things considered, a fairly limited range of application. These units are not equipped with pulverizers or screens. The earth, which is deposited in a hopper, is premixed by gravity with a stabilizer by means of an integrated proportioning system. It is then moved by conveyor belt to the mixer where dry and wet mixing are carried out. A storage hopper distributes the earth within the mould where it is hypercompressed and then automatically ejected in the form of blocks. These units dispose of a system of slide moulds which cannot be used to produce hollow or cellular blocks. Being costly and having only moderate output, their future appears to be confined to limited markets.

#### (d) *Industrial production units*

For several years the market has seen the arrival of a whole range of fully equipped standing industrial production units of a limited size. These industrial units operate on single or double static compression or dynamic compression principles. The list of products that can be manufactured by them is not limited to the small blocks which almost all the other presses can turn out. The list, thus, includes all the forms of concrete blocks and burnt bricks which can also be made using stabilized earth, including hollow blocks and perforated bricks. This manufacturing equipment is as yet only intended for a limited market. Only massive construction programmes can ensure that the investments involved can be recovered and the cost of producing the blocks significantly reduced. This type of press is currently used in countries



such as Algeria, Brazil, Gabon, Mexico and Nigeria. There are two types of industrial production units.

(i) Hydraulic presses

Wholly automatic hydraulic industrial units come in several sizes. At the small end of the range, units such as the Ceramaster are fairly compact. This type is still in the prototype stage. Units of average size like the Luxor, formerly the Tecmor have been reconditioned and can handle production technology with ease. They use double compaction. Finally, the heaviest hydraulic industrial presses are veritable turnkey plants and are available in several sizes. Today, it appears that only a few operational plants exist in all the world. Considerable secrecy surrounds the operation of these industrial units. The Latorex and Krupp type units make use of a stabilization process based, respectively, on hydrated lime and quicklime. In both cases the technology has much in common with that of the silica-limestone industry from which it has been adapted. The pressures applied are in the hyperpressure and megapressure ranges. The blocks are dried in an autoclave and operation is entirely automatic. In Nigeria and the Philippines, major problems have been encountered with this type of heavy hydraulic industrial plant. The technology that has been developed is very sophisticated indeed, and requires faultless technical control and supervision of the organization of the work.

(ii) Combined hydraulic and mechanical presses

These are equivalent to a totally automated factory. A prototype of one is currently operational in France, in the construction of the experimental Village Terre on l'Ile d'Abeau near Lyon. These presses have been adapted from concrete-block presses. The process combines mechanical vibration and hydraulic compaction technology. By this is meant vibration at a high frequency, low amplitude (1.5-2 mm) and hydraulic compression at low pressure ( $20 \text{ daN/cm}^2$ ). The frequency of vibration and the pressure of compaction can be regulated to match the soil. The production cycle consists of the following operations: filling the mould from a drawer; vibration; lowering of the plunger; raising the mould; removal of the material from the mould with withdrawal of the plunger; and removal of the fresh product on a conveyor. The duration of the entire cycle is of the order of 40 seconds. This type of press can produce solid and hollow blocks ( $20 \times 20 \times 40$  or  $50 \text{ cm}$ ) at the rate of 1000-1500 per day or 2000-2500 solid blocks per day. This represents a decrease of approximately 50 per cent with respect to concrete blocks. The smooth operation of these presses requires, moreover, an adequate technological environment and well-trained and experienced operators and maintenance personnel. A tendency towards a reduction in size is currently under way. One example of this trend includes the French Dynater machine, currently under trial.

## PART FIVE

### BIBLIOGRAPHY

Adam, E.F.A., *Stabilised Soil Blocks for Low Cost Housing in the Sudan* (Hatfield, Hatfield Polytechnic, 1982).

Adam, J.A., and others, *Architektur der Vergänglichkeit. Lehmbauten der Dritte Welt* (München, Die Neue Sammlung, Staatliches Museum für angewandte Kunst, 1981).

Adam, J.A., *Wohn-und Siedlungsformen im Süden Marokkos* (München, Georg D.W. Callwey, 1982).

ADAUA, "Chantier d'essais", *Programme d'habitat populaire à Rosso* (Geneva, ADAUA, 1977).

ADAUA, "Experimental work site", *Programme of Dwellings for the People in Rosso* (Geneva, ADAUA, 1977).

Adobe News, "Adobe codes from around the world west" (Albuquerque, Adobe News, 1982).

Alfshar, F., and others, "Mobilizing indigenous resources for earthquake construction", in *International Journal IASH* (New York, Pergamon Press, 1978).

Agarwal, A., *Batir en terre. Le potentiel des matériaux à base de terre pour l'habitat du tiers monde* (London, Earthscan, 1981).

Agarwal, M., *Mud, Mud. The Potential of Earth-based Materials for Third World Housing* (London, Earthscan, 1981).

Agence française pour l'aménagement et le développement à l'étranger (ACA), *Opération expérimentale d'habitat à Banconi. Bamako-Mali. Rapport de la première phase de réalisation* (Paris, ACA, 1982).

Ahmed Hassan Hamid. *Asphalt-based Coating* (Roorkee, CBRI, 1972).

Alaoui, H., and Chandellier, J., "Agrément et matériaux locaux", *Actes du séminaire sur la construction en matériaux locaux Marrakech, 25-26 avril 1986* (Marrakech, ERAC, DCTS Ministère de l'Habitat, 1987), pp.34-40.

Albenque, M., and Hiebel, R., "Briques de terre cuite et briques en argile stabilisée appropriées à l'habitat économique dans les pays en voie de développement", *Comptes-rendus du colloque international "L'habitat économique dans les pays en développement : matériaux, techniques de construction, composants" Paris, 25-27 janvier 1983* (Paris, Presses de l'ENPC, 1983), vol. 1, pp.15-20.

Alcock, A., *Swischcrete; Notes on Stabilised Cement-earth Building in the Gold Coast* (Kumasi, BRS, 1953).

Amen, A.K., and Gbeckor-Kove, *The Improved Mud Wall Building* (Kumasi, University of Science and Technology, n.d.).

Andersson, L.A., Johansson, B., and Astrand, J., *Torba stabilisée au ciment. Etude expérimentale d'un sol d'origine locale et développement*



de techniques pour sa mise en oeuvre comme matériau de construction (Lund, University of Lund, 1982)

Andoh Allé, J., "La terre stabilisée, ou géobéton, un matériau approprié", *Bulletin du LBTP* (Abidjan) (1986), No. 3. pp.86-102.

Archer, J., and Archer, G., *Dirt Cheap; the Mud Bricks Book* (Melbourne, Compendium Pty, 1980).

"Architecture en terre ou l'avenir d'une tradition millénaire", *Construire* (Algiers) (1983), Nos.2 and 3.

Arrigone, J.L., *Appropriate Technology Adobe Construction. A Research and Demonstration Project on the Use of Adobe for Low-cost Housing Construction*, CSIR Research Report, No. BBR 629 (Pretoria, NBRI, CSIR, 1986).

Arzoumanian, V., and Bardou, P., *Architectures de terre* (Marseille, Editions Parenthèses, 1978).

Aslam, M., and Satya, R.C., *Technical Notes on Surface Waterproofing of Mud Walls* (Roorkee, CBRI, 1973).

Ayala, V., "Etude sur la stabilisation des sols en terre des diatomées et à la chaux pour son utilisation en construction des logements économiques", *Proceedings of a Symposium held in Nairobi, from 7 to 14 November 1983, on Appropriate Building Materials for Low-cost Housing: African Region* (London and New York, E. and F.N. Spon, 1985), vol. 2, pp.45-51.

Bardou, P., and Arzoumanian, V., *Arquitecturas de Adobe* (Barcelona, Editorial Gustavo Gili, 1979).

Barns, C.G., *The Sod House* (Lincoln and London, Bison Book, University of Nebraska Press, 1970).

BCEOM, *La construction en béton de terre* (Paris, BCEOM, Service de l'Habitat, 1952).

Belmans, D., and others, *Recommandations pour la conception des bâtiments du Village Terre* (Grenoble, AGRA, Plan Construction, 1982).

Berliat, J.C., "La presse à géobéton LBTP-IPNETP", *Bulletin du LBTP* (Abidjan) (1986), No. 3, pp.75-85.

Blondet, M., Torrealva, D., and Mendoza, F., "Evaluation of shaking table tests to simulated seismic behaviour of adobe masonry dwellings", *Proceedings of the 10th Triennial Congress of the International Council for Building Research Studies and Documentation on Shelter for the Homeless in Developing Countries 22-26 September 1986, Washington* (Gaithersburg, CIB, 1986), vol. 5, pp.1607-1617.

"Bloquera del CTA", *Boletín*, No. 2 (Asunción, Universidad Católica Nuestra Señora de la Asunción, 1985).

Bona, T., *Manuel des constructions rurales* (s.l., Librairie agricole de la maison rurale, 1950).

Boonstra, J.L., *Soil Cement Handbook. A Practical Guide to Soil Cement Applications* (Mbabane, UNDP, UNCHS (Habitat) and



Government of the Kingdom of Swaziland, Ministry of Natural Resources, Land Utilization and Energy, 1985).

Boudreau, E.H., *Making the Adobe Brick* (Berkeley, CA, Fifth Street Press, 1974).

Boufous, M., "Technologie du pisé", *Actes du séminaire sur la construction en matériaux locaux. Marrakech, 25-26 avril, 1986* (Marrakech, ERAC, DCTC, Ministère de l'Habitat, 1987), pp.189-196.

Bourdier, J.P., and Minh-Ha, T.T., *African Spaces. Designs for Living in Upper Volta* (New York, Africana Publishing Company, 1978).

Brigaux, G., *La maçonnerie* (Paris, Eyrolles, 1976).

Building Research Unit, "Soil (mud) blocks", *BRU Data Sheet*, No. B.4.1 (Dar-es-Salaam, BRU, Ministry of Lands, Housing and Urban Development, n.d.).

Building Research Unit (BRU), "Stabilized soil block walls", *BRU Data Sheet*, No. E.4.1 (Dar-es-Salaam, BRU, Ministry of Lands, Housing and Urban Development, n.d.).

Building Research Unit (BRU), "Stabilized solid soil walls", *BRU Data Sheet*, No. E.5.1 (Dar-es-Salaam, BRU, Ministry of Lands, Housing and Urban Development, n.d.).

Bunting, B., *Early Architecture in New Mexico* (Albuquerque, University of New Mexico Press, 1976).

Bunting, B., and Lazar, A., *Of Earth and Timbers Made* (Albuquerque, University of New Mexico Press, 1975).

Bunting, B., and others, *Taos Adobes* (Santa Fe, Fort Burgwin Research Centre, Museum of New Mexico, 1975).

Bureau de l'habitat rural, *Surfaçage des parpaings de terre et badigeonnage* (Dakar, Direction de l'habitat et de l'urbanisme TP et transports, 1963).

Bustamante, O.C., and Kamimoto, R.Y., *Diseño Sismo-resistente de Muros de Adobe* (Lima, n.d.).

Cain, A., "Earth for third world habitat. Choice of materials", *Proceedings of the International Conference on Economical Housing in Developing Countries: Materials, Construction Techniques and Components, Paris, January 25-27 1983* (Paris, Presses de l'ENPC, 1983), vol. 2, pp.19-24.

CARE, *Soil-cement Block. Instruction Manual for the Soil-cement Block Moulding Machine and Soil-cement Block Construction* (Lahore, Department of Civil Engineering, University of Engineering and Technology, 1970).

"Casas de tierra", *MINKA*, No. 9 (Huancayo, 1984).

Central Building Research Institute (CBRI), *Live Better with Mud and Thatch - Improved Rural Houses* (Roorkae, CBRI, 1985).

CEPED, *Relatorio Ensaio de Formas* (Rio de Janeiro, 1970).

CEPED, and THABA, *Manual de Construção com Solo-cimento* (São Paulo, ABCP, 1984).

CEPED and THABA, *Manual Prático de Construção com Solo-cimento* (Rio de Janeiro, 1978).

Cerda Antúñez, E., *Casa Campesina de Suelo Cemento* (Bogotá, Centro Interamericano de Vivienda y Plancamiento, 1963).

Chatterji, A.K., "Les efflorescences dans les ouvrages en briques", in *Bâtiment international* (Paris, CSTB, 1970).

CINVA, *Le béton de terre stabilisé et son emploi dans les travaux de construction* (New York, United Nations, 1964).

Clifton, J.R., Brown, P.W., and Robbins, C.R., *Methods for Characterizing Adobe Building Materials* (Washington, D.C., U.S. Department of Commerce, 1978).

Clifton, J.R., and David, F.L., *Mechanical Properties of Adobe* (Washington, D.C., U.S. Department of Commerce, 1979).

CNERIB, "Industrialisation de la fabrication de blocs de béton de terre", *Comptes-rendus du colloque international : Matériaux, techniques et économie de la construction dans les pays en développement*, Paris, 9-10-11 décembre 1986 (Paris, CSTB, Plan Construction, Presses de l'ENPC, 1986), vol. 1, pp.23-29.

Coad, J.R., "Lime-stabilised soil building blocks", *Building Research and Practice* (Watford), March/April 1979, No. R1, pp.80- 88.

*Construcción de Vivienda Económica con Bloques de Suelo Compactado - Prototipo "A"* (Asunción, Universidad Católica Nuestra Señora de la Asunción, 1984).

Coungny, G., "Les terres à géobéton en Côte d'Ivoire : caractéristiques, prospection et exploitation", *Bulletin du LBTP* (Abidjan) (1986), No. 3, pp.47-68.

CRATerre and USMG, "Cinq années d'habitat social à Mayotte", *Comptes-rendus du colloque international : Matériaux, techniques et économie de la construction dans les pays en développement*. Paris 9-10-11 décembre 1986 (Paris, CSTB Plan Construction, Presses de l'ENPC, 1986), vol. 1, pp.59-65.

CRYRZA and PREVI, *Manual para la Construcción de Viviendas con Adobe* (Lima, Oficina Nacional de Desarrollo Comunal, 1971).

Cuny, F.C., *Improvement of Adobe Houses in Peru: a Guide to Technical Considerations for Agencies* (Dallas, INTERTECH, 1979).

CVS-GRET, *Innovations in Mud Walls* (Paris, 1985).

Cytryn, S., *Construcción con Tierra. Sus Principios y Aplicación para Viviendas* (Mexico City, Centro Regional de Ayuda Técnica, 1964).

Cytryn, S., "Earth for homes", *Ideas and Methods Exchange*, No. 22 (Washington, D.C., Department of Housing and Urban Development, Office of International Affairs, 1955).

Cytryn, S., *Soil Construction. Its Principles and Application for Housing* (Jerusalem, The Weizman Science Press of Israel, 1957).

Dansou, A., "La terre stabilisée, matériau de construction", *Bulletin d'information* (Lomé, CCL, 1975), Nos. 2 and 3.



Dayre, M., *Commentaires de la fiche "Laboratoire tiers monde" UPA 6, concernant la recherche "protection du matériau terre"* (Grenoble, AGRA, 1982).

Dayre, M., *Conseils pour la réalisation d'enduits de façade* (Privas, DDE Ardèche, 1982).

Dayre, M., "Protection du matériau terre", *Comptes-rendus du colloque international, "L'habitat économique dans les pays en développement : matériaux, techniques de construction, composants"*, Paris, 25-27 janvier 1983 (Paris, Presses de l'ENPC, 1983), vol. 1, pp.37-42.

Dayre, M., and others, *Toitures enterre* (Paris, Rexcoop, 1986), tome 1. Arcs, voûtes et coupoles.

Delarue, J., "Etude du pisé de ciment au Maroc", *Bulletin RILEM* (Paris) (1954).

Delaval, B., *La construction en béton de terre* (Alger, LNTBP, 1971).

Denyer, S., *African Traditional Architecture: an Historical and Geographical Perspective* (New York, Africana Publishing Company, 1978).

Des Lauriers, T., *Projet Addis-Abéba* (Addis-Abéba, REX-COOP/MUDH, 1983).

Dethier, J., *Arquitetura de Terra ou o Futuro de uma Tradição Milenaira* (Rio de Janeiro, Avenir Editors Limitada, 1984).

Dethier, J., *Des architectures de terre, ou l'avenir d'une tradition millenaire* (Paris, CCI, 1981).

Dethier, J., *Down to Earth; Mud Architecture: an Old Idea, a New Future* (London, Thames and Hudson, 1982).

Dethier, J., *Lehmarchitektur Die Zukunft einer vergessenes Bautradition* (München, Prestel, 1982).

D'Hooghe, L., "Les maisons économiques de Nyamirambo construites par le projet urbain de COOPIBO à Kigali, Rwanda", *Inventaire, expériences des techniques dans des projets ONG* (Leuven, ATOL, 1984).

Díaz-Romeral, J., and others, "Mechanical and functional behaviour of earth samples", *Proceedings of the Tenth Triennial Congress of the International Council for Building Research, Studies and Documentation on Shelter for the Homeless in Developing Countries, Washington* (Gaithersburg, CIB 86, 1986), vol. 4, pp.1482-1488.

Doat, P., and others, *Construire en terre* (Paris, Editions Alternatives, 1985).

Doe, Bruce A., "La terre stabilisée : technique de mise en oeuvre", *Bulletin d'information* (Lomé, CCL, 1986), No. 5, pp.31- 42.

Dolphyn, J., *Architecture traditionnelle en Côte d'Ivoire. Matières, matériaux, mise en oeuvre* (Brussels, Institut Supérieure d'Architecture de l'Etat "La Cambre", 1981).

Dreyfus, J., *Manuel de la construction en terre stabilisée en AOF* (Dakar, Haut commissariat en AOF, 1954).



Dreyfus, J., "Peintures et moyens de protection divers pour construction en terre ou en terre stabilisée", *Peintures, pigments, vernis*.

Duriez, M., and Arrambide, J., *Etude sur les enduits et rejointements* (Paris, Dunod, 1962).

"Earth construction", *Al-Mohandis*, No. 7 (Riyadh, 1988).

"Earth construction technologies in developing countries", *Proceedings of the Arab League Seminar on the Use of Clay in Housing Construction and New Technologies*, Tunis, 8-10 September 1986 (Nairobi, UNCHS (Habitat) 1986).

Easton, D., *The Rammed Earth Experience* (Wilseyville, Blue Mountain Press, 1982).

Ebert, W.M., *Home Sweet Dome* (Frankfurt am Main, Dieter Fricke GmH, 1981).

Edwards, R., Lin Wei-Hao, *Mud Brick and Earth Building. The Chinese Way* (Kuranda, Australia, The Rams Skull Press, 1984).

Elabbadi, A., *Mécanisme de durcissement des briques en terre stabilisée à la chaux. Conditions de cure et choix des terres* (Paris, Ecole Nationale Supérieure des Mines de Paris, 1986).

*El Suelo como Material de Construcción* (Mexico City, CEPAL/PNUMA, 1980).

Epnoevi-Qo, F., "La protection des murs en banco", *Bulletin d'information* (Lomé, CCL, 1987), No. 9, pp.44-57.

Escoffery Alemán, F.A., *Casa de Adobe Resistente a Sismos y Vientos como Solución al Problema de Vivienda Rural en Panamá* (Panama, Universidad Santa María la Antigua, 1981).

Estève, J., "Arcs, voûtes et dômes", *Actes du séminaire sur la construction en matériaux locaux, Marrakech, 25-26 avril 1986* (Marrakech, ERAC, DTCD, Ministère de l'Habitat, 1987), pp.175-180.

Eurin, P., and Rubaud, M., "Etude exploratoire de quelques techniques de stabilisation chimique de la terre", *Proceedings of a Seminar, held in Nairobi, from 7 to 14 November 1983, on Appropriate Building Materials for Low-cost Housing: African Region* (London and New York, E. and F.N., Spon, 1985), vol. 2, pp.52-59.

Fathy, H.M., *Architecture for the Poor. An Experiment in Rural Egypt*: (Chicago, University of Chicago Press, 1973).

Fathy, H.M., *Construire avec le peuple. Histoire d'un village d'Egypte: Gournia* (Paris, Editions Jérôme Martineau, 1970).

Fathy, H.M., "Thermomechanical analysis of some Egyptian clays and clay/sand mixtures", *Proceedings of a Symposium held in Nairobi, from 7 to 14 November 1983, on Appropriate Building Materials for Low-cost Housing: African Region* (London and New York, E. and F.N. Spon, 1985), pp.12-17.

Ferm, R., *Stabilized Earth Construction. An Instructional Manual* (Washington, D.C., IFEC, 1985).

Fernandez, J.A., "Rationalisation du système "Bajareque" pour la construction d'habitations dans les pays en voie de développement",

*Proceedings of the 10th Triennial Congress of the International Council for Building Research, Studies and Documentation on "Shelter for the Homeless in Developing Countries, 22-26 September 1986, Washington (Gaithersburg, CIB 86, 1986), vol. 4, pp.1334- 1345.*

Fierens, P., and others, "Fabrication de matériaux de construction à partir de matières premières zairoises peu onéreuses", *Proceedings of a Seminar, held in Nairobi, from 7 to 14 November 1983, on Appropriate Building Materials for Low-cost Housing: African Region* (London and New York, E. and F.N. Spon, 1985), pp.43-52.

Fitzmaurice, R., *Manual on Stabilized Soil Construction for Housing* (New York, United Nations, 1985).

Fitzmaurice, R., *Manual sobre Construcción de Viviendas con Tierras Estabilizadas* (New York, United Nations, 1959).

Fitzmaurice, R., *Manuel de construction d'habitations en béton de terrestabilisé* (New York, United Nations, 1959).

Foti, M., and Gilibert, A., "Study of building elements suitable for self-production", *Proceedings of a Symposium held in Bangkok, from 20-26 January 1987, on Building Materials for Low-income Housing, Asia and Pacific Region* (London, E. and F.N. Spon, 1987), pp.259-267.

Frescura, F., *Rural Shelter in Southern Africa. A Survey of the Architecture, House Forms and Construction Methods of the Black Rural Peoples of Southern Africa* (Johannesburg, Ravan Press, 1981).

Fullerton, R.L., *Sundried Block in Low-cost Housing* (Kumasi, University of Science and Technology, 1966).

Gaidieri, E., *Le meraviglie dell'architettura in terra cruda* (Roma, Editori Laterza, 1982).

Gano, E.J., *Adobe Designs* (Pueblo, CO, Gano, 1980).

Gardi, R., *Maisons africaines: L'art traditionnel de bâtir en Afrique occidentale* (Paris and Bruxelles, Elsevier Sequoia, 1974).

Garrison, P., *How to Build Adobe Houses ...* (Blue Ridge Summit, Tab Books, 1979).

Gary, V., and Macrae, A., *Mud, Space and Spirit* (Santa Barbara, CA, Capra Press, 1976).

German Appropriate Technology Exchange (GATE), *Lehmarkonstruktion, Rückblick-Ausblick* (Frankfurt am Main, GATE, 1981).

GATE and GTZ, *Low-cost Self-help Housing. Foundation, Statics, Protection, Wall Construction using Pisé de Terre, Roof Construction* (Eschborn, GATE and GTZ, 1980).

Gieth, T., and others, *Construir con Barro - parte A - El Barro como Material de Construcción* (Asunción, Universidad Católica Nuestra Señora de la Asunción, 1987).

Government of Mexico, *Cartilla de Reconstrucción para la Vivienda de Adobe* (Mexico City, Secretaría de Desarrollo Urbano y Ecología, n.d.).

Government of Peru, *Adobe, Diseño y Construcción* (Lima, Ministerio de Vivienda y Construcción, n.d.).



Government of Peru, *Construcción en Adobe* (Lima, Ministerio de Vivienda y Construcción, 1971).

Government of Peru, *Recomendaciones Técnicas para la Reparación en Edificaciones de Adobe y Quicha Dañadas por Movimientos Sísmicos* (Lima, Ministerio de Vivienda y Construcción, 1974).

Gratiwick, R.T., *Dampness in Buildings* (London, Crosby, n.d.).

Grésillon, J.M., "Etude de l'aptitude des sols à la stabilisation au ciment. Application à la construction", *Annales de l'ITBTP* (Paris) (1987), No. 361.

Grésillon, J.M., "Etude sur la stabilisation et la compression des terres pour leur utilisation dans la construction", *Annales de l'ITBTP* (Paris) (1976), No. 339.

Grésillon, J.M., "Habitat en terre stabilisée au Burkina. Analyse statistique", *Comptes-rendus du colloque international : Matériaux techniques et économique de la construction dans les pays en développement, Paris, 9-10-11 décembre, 1986* (Paris, CSTB, Plan Construction, Presses de l'ENPC, 1986), vol. 1, pp.224-230.

Grésillon, J.M., and Dourthe, V., "Un matériau nouveau pour l'habitat rural: la brique bicouche", *Bulletin technique de l'Ecole Inter Etats d'Ingenieurs et de l'Equipement Rural* (Ougadougou) (1981), No. 7.

Greth, T., and others, *Innovaciones del CTA. Participación en la Segunda Exposición y Concurso Nacional de Invenciones e Innovaciones* (Asunción, Universidad Católica Nuestra Señora de la Asunción, 1987).

Groben, E.W., *Adobe Architecture, its Design and Construction* (New York, U.S. Department of Agriculture, Forest Service, 1941).

Guidoni, E., *Primitive Architecture* (New York, Harry N. Abrams, 1975).

Guillaud, H., *Histoire et actualité de la construction en terre* (Marseille, UPA Marseille - Luminy, 1980).

Guillaud, H., and others, *Marrakech 87. Habitat en terre* (Grenoble, CRATerre, 1987).

Hammond, A.A., "Foundations for earth buildings in the Tropics", *Bâtiment International* (London, CIB, 1984), pp.30-36.

Hammond, A.A., "Prolongation de la durée de vie des constructions en terre sous les tropiques", *Bâtiment Build International* (Paris) (1973), No. 3, pp.167-179.

Hammond, A.A., "Prolonging the life of earth buildings in the tropics", *Building Research and Practice* (London, CIB, 1973).

Hartkopf, V., *Indigenous Building Techniques of Peru and Their Potential for Improvement to Better Withstand Earthquakes* (Washington, D.C., USAID, 1981).

Hartkopf, V., *Técnicas de Construcción Autóctonas del Perú y sus Potenciales de Mejora para Resistir más adecuadamente los Sismos* (Washington, D.C., USAID, 1985).



Hays, A., Matuk, S., and Vitoux, F., *Técnicas Mixtas de Construcción con Tierra* (Paris, Rexcoop, 1986).

Hecht, H., *Dessins d'une presse manuelle pour parpaings de terre* (Eschborn, GATE and GTZ, 1979).

Herbement, O., Mariotti, C., and Nouari, L., *Rapport sur le programme d'essais préliminaires de pisés améliorés* (Casablanca, LPEE, 1977).

Hernández, O.B., and Meli, R., "El refuerzo en construcciones de adobe en zonas sísmicas", *Revista Especializada en Espacios Educativos*, No. 59-60 (Mexico City, 1983).

Herrera Delgado and others, *La Tierra en la Arquitectura : una Revalorización* (Mexicali, Universidad Autonoma de Baja California, 1978).

Holmes, "Mud brick roofs", *Ideas and Methods Exchange*, No. 42 (Washington, D.C., Department of Housing Service and Urban Development, 1957).

Holmgren, L., *Some Experiments on Stabilized Soil Blocks* (Addis Ababa, Building Centre, 1964).

Hopson, R.C., *Adobe, a Comprehensive Bibliography* (Santa Fe, The Lightning Tree, 1980).

Houben, H., "Modern compressed earth block production equipment", *Communications au séminaire régional sur l'habitat spontané et l'habitat économique. Addis Abeba, 18-21 novembre, 1985* (Paris, UNESCO, MUDH, CEBTP, 1987), pp.20-39.

Houben, H., and Doat, P., "Construir en tierra", *Revista Especializada en Espacios Educativos*, No. 59-60 (Mexico City, 1983).

Houben, H., and Guillaud, H., "Traité de construction en terre", *L'encyclopédie de la construction en terre* (Marseilles, Editions Parenthèses, for CRATerre, 1988).

Houben, H., and others, *Construction en terre crue : les matériels français* (Grenoble, CRATerre, 1987).

Houben, H., and others, *Raw Earth Construction: the French Equipment* (Grenoble, CRATerre, 1987).

Houben, H., and Verney, P.E., *Blocs de terre comprimée : choix du matériel de production* (Brussels, CDI, 1988).

Houben, H., and Verney, P.E., *Compressed Earth Blocks: Selection of Production Equipment* (Brussels, CDI, 1988).

Housing and Home Finance Agency, "A cheap coating for unstabilized earth walls", *Ideas and Methods Exchange* (Washington, D.C., Office of International Affairs, 1961).

Howard, T., *Owner-building and Earth Architecture* (Melbourne, University of Melbourne, 1984).

Hudson Clough, R.A., *A Qualitative Comparison of Rammed Earth and Sun-dried Adobe Brick*, Publications in Engineering, No. 4 (Albuquerque, University of New Mexico, 1950).

Indian Institute of Science (IIS), *The ASTRAM Soil-block Machine* (Bangalore, ASTRAM, IIS, n.d.).

INIAVI, *Construyendo con Adobe* (Lima, 1976).

ININVI, *Construcciones de Adobe. Disposiciones Especiales para Diseño Sismo-resistente* (Lima, n.d.).

International Institute of Housing Technology (IIHT), *The Manufacture of Asphalt Emulsion Stabilized Soil Bricks and Brick Maker's Manual* (Fresno, CA, IIHT, 1972).

International Workshop on Earthen Buildings in Seismic Areas. *Proceedings of the International Workshop held at Albuquerque, New Mexico, May 24-28, 1981* (Albuquerque, University of New Mexico, 1981), 3 vols.

INTERTECT, University of New Mexico, *Vernacular Housing in Seismic Zones of India* (Washington, D.C., USAID, 1984).

IPT, *Utilização de Blocos de Solo-cimento na Construção de Habitações* (São Paulo, 1980).

Iterbeke, M., and Jacobus, P., *Project on Low-cost Housing. Rural Demonstration House, Chumpuang, Thailand, May 1987* (Leuven, PGC-HS-KUL, 1987).

Jagadish, K.S., and others, *Better Houses with Mud - A Manual of Alternative Building Construction*, Alternative Building Series, No. 7 (Bangalore, ASTRA, Indian Institute of Science, 1983).

Jalal, M., "Expérimentation du béton de terre et son utilisation dans les chantiers expérimentaux de la délégation du Ministère de l'Habitat et de l'Aménagement du Territoire", *Minutes du colloque sur l'authenticité architecturale dans le sud du royaume et l'utilisation de matériaux locaux de construction. Ouazazate, 6-7 juin 1980* (Rabat, Ministère de l'Habitat et de l'Aménagement du Territoire, 1980).

Jamal, S.Q., and Sheikh, A.S., "The use and performance of soil stabilized building blocks in flood affected rural areas", *Proceedings of a Symposium, held in Bangkok, from 20 to 26 January 1987, on Building Materials for Low-cost Housing, Asian and Pacific Region* (London, E. and F.N. Spon, 1987), pp.302-309.

Joffroy, T., "Programme "terre", *Center of Sciences for Villages, Wardha (Inde)* (Paris, GRET, 1984).

Kafescioglu, R., and others, "Adobe blocks stabilized with gypsum", *Proceedings of a Symposium held in Nairobi, from 7 to 14 November, 1983, on Appropriate Building Materials for Low-cost Housing, African Region* (London and New York, E. and F.N. Spon, 1985), pp.3-11.

Kahane, J., *Local Materials. A Self Builder's Manual* (London, Publication Distribution Co-operative, 1978).

Kajaste-Rudnitski, J., *On Plastering of Mud Block Walls for Low-cost Housing*, BRU Working Report, No. WR 38 (Dar-es-Salaam, Building Research Unit, Ministry of Lands, Housing and Urban Development, 1984).



Kateregga, J.K., "Improvement and use of earth construction products for low-cost housing", *Proceedings of a Symposium held in Nairobi, from 7 to 14 November 1983, on Appropriate Building Materials for Low-cost Housing, African Region* (London and New York, E. and F.N. Spon, 1985), pp.23-33.

Kern, K., *Rammed Earth* (s.l., Owner Builder Publications, 1980).

Kern, K., *The Owner Built Home* (New York, Charles Scribner and Sons, 1975).

Kienlin, "Le béton de terre", *Revue génie militaire* (Paris, 1947).

Laboratoire fédéral d'essai des matériaux et institut de recherches (LFEMIR), *Directives pour l'exécution de crépissages* (Dubendorf, LFEMIR, 1968).

Laurent, J.P., "Propriétés thermiques du matériau terre", *Cahiers du CSTB, Etudes et recherches* (Paris, 1987), No. 2156.

Laurent, J.P., Rubaud, M., and N'Dong, D., "La durabilité des protections sur terre stabilisée : l'expérience des "murets Dreyfus" de Dakar", *Cahiers du CSTB* (Paris, Rexcoop, 1985), No. 2022.

*Le béton de terre stabilisé. Son emploi dans la construction* (New York, United Nations, 1964).

Lenner, H., and Niernmann, M., *Lehmarchitektur in Spanien und Afrika* (s.l., Karl Robert Langewiesche, 1980).

Letertre and Renaud, *Technologie du bâtiment. Oros oeuvre. Travaux de maçonnerie et finitions* (Paris, Foucher, 1978).

L'Hermite, R., *Au pied du mur* (Paris, Eyrolles, 1969).

Lumpkins, W., *Casa del Sol* (Santa Fe, Santa Fe Publishing Co., 1981).

Lumpkins, W., *Adobe, Past and Present* (Albuquerque, University of New Mexico, 1974).

Lunt, M.G., "Stabilised soil blocks for building", *Overseas Building Notes*, No. 184 (Watford, BRE, 1980).

Maggiolo, R.O., *Construcción con Tierra* (Lima, Comisión Ejecutiva Interministerial de Cooperación Popular, 1964).

*Maisons en terre*, Collections techniques américains (Paris, CRET, 1956).

*Making Building Blocks with the CINVA-Ram Block Press* (New York, VITA, 1966).

*Making Mud Houses More Durable*, Housing for Million Series, No. 1 (New Delhi, National Building Organisation, n.d.).

Manandhar, R., "Dome and vault construction in mud bricks without using formwork: an experience from a project of low-cost, low-energy house with popular participation in Victoria", *Proceedings of the International Conference on Economical Housing in Developing Countries: Materials, Construction Techniques, Components, Paris, January 25-27 1983* (Paris, Presses de l'ENPC, 1983), vol. 1, pp.61-67.

Manson, J.L., and Weller, H.O., *Building in Cob and Pisé de Terre* (s.l., BRB, 1922).



Mariotti, M., "Programme expérimental sur badigeons de protection des murs en béton de terre", *Proceedings of a Seminar held in Nairobi, from 7 to 14 November 1983, on Appropriate Building Materials for Low-cost Housing, African Region* (London and New York, E. and F.N. Spon, 1985), pp.402-415.

Mariotti, M., "Recommendations for cement stabilized soil concrete", *Proceedings of a Symposium held in Khartoum, February 20th-23rd 1980* (Khartoum, Faculty of Arts, University of Khartoum, 1981).

Markus, T.A., and others, *Stabilised Soil: an Under-utilised Resource for Low-cost Building in Developing Countries* (Glasgow, University of Strathclyde, 1979).

Martin, M., *Construction en terre : renforcement à l'aide de fibres végétales. Mise en oeuvre, comportement mécanique, durabilité* (Paris, Université Pierre et Marie Curie, Ecole Nationale Supérieure des Mines de Paris, 1985).

Martin, M., and others, *Contribution au contrôle de production des blocs de terre compressée : mise au point et proposition d'une procédure d'écrasement au laboratoire* (Casablanca, Ministère de l'Équipement et de la Formation Professionnelle et de la Formation des Cadres, n.d.).

Mathur, G.C., "Durability and service life of much houses", *Proceedings of a Symposium, held in Bangkok, from 20 to 26 January 1987, on Building Material for Low-cost Housing: Asia and Pacific Region* (London, E. and F.N. Spon, 1987), pp.313-320.

Mathur, G.C., *Report on Comparative Tests on Water-proof Renderings for Mud Walls* (New Delhi, National Building Organisation, 1985).

Matuk, S., *Architecture traditionnelle en terre au Pérou* (Paris, Ecole Nationale Supérieure des Beaux-Arts, 1978).

Matuk, S., Hays, A., Arcos, C.N., and Vildoso, C.A., *Cuadernos de Construcción Popular* (Lima, CRATerre América Latina, 1986).

McCalamont, J.R., *Experimental Results with Rammed Earth Construction* (St. Joseph, American Society of Agriculture Engineers, 1943).

McHenry, P.G., *Adobe Build it Yourself* (Tucson, The University of Arizona Press, 1974).

McHenry, P.G., *Adobe and Rammed Earth Buildings. Design and Construction* (New York, Wiley Interscience, 1984).

McNeal, D.H., and Jones, R.A., *Baldosas de Suelo-cemento para Pisos* (Bogotá, Unión Panamericana, 1959).

*Memorias. Seminario Latinoamericano de Construcciones de Tierra en Areas Sísmicas, Lima, Perú, 23-27 Mayo, 1983* (Lima, Pontificia Universidad Católica del Perú, 1983).

Mesbah, A., Olivier, M., and Simon, D., *Tortures en terre* (Paris, Rexcoop, 1987), tome 2, Expérimentation et calcul d'une coupole.

Middleton, G.F., *Building Your House of Earth (a Manual of Earth Wall Construction* (Birregurra South, Compendium, 1979).

Middleton, G.F., and Schneider, L.M., *Earth-wall Construction* (Chatswood, Australia, National Building Technology Centre, 1987).

Miller, L., and Miller, D., *Manual for Building a Rammed Earth Wall* (Greeley, CO, Rammed Earth Houses, 1980).

Miller, T., and others, *Lehmbaufibel* (Weimar, Forschungsgemeinschaften Hochschule, 1947).

Ministère des affaires culturelles, *Vocabulaire de l'architecture* (Paris, Ministère des affaires culturelles, 1972).

Minke, G., *Alternatives Bauen* (Kassel, Gesamthochschule, 1980).

Minke, G., "Low-cost housing-appropriate construction techniques with loam, sand and plant stabilized earth", *Proceedings of the International Conference on Economical Housing in Developing Countries: Materials, Construction Techniques, Components, Paris January 25-27 1983* (Paris, Presses de l'ENPC, 1983), vol. 1, pp.81-86.

Morales Morales, R., Sanchez Orlano, A., and Kamimoto, R.Y., *Estructuras. Proyecto de Bloque Estabilizado* (Lima, Centenario Universidad Nacional de Ingeniería, 1976).

Morán Buitrón, *Uso del Ferrocemento en la Construcción de Bajo Costo* (Quito, Pontificia Universidad Católica del Ecuador, 1984).

Moriarty, J.P., and Therkildsen, O., *Lateritic Soil-cement as a Building Material* (Dar-es-Salaam, Building Research Unit, Ministry of Lands, Housing and Urban Development, 1973).

Morse, R., "Plastic-C coating. Plastic-B/C/D", Private communication, (New York, 1977).

Moughtin, J.C., *Hausa Architecture* (London, Ethnographica, 1985).

Mukerji, K., and Bahlmann, H., *Laterite for Building* (Strasbourg, IBT, 1978).

Mukerji, K., Houben, H., and Verney, P.E., *Soil Block Presses. Production Information* (Eschborn, GATE, 1988).

Museum of New Mexico, "Adobe past and present", in *El Palacio* (Santa Fe, 1974).

Nagarkar, P.K., Khole, V.C., and Gupta, S.C., "Building bricks from industrial waste (flyash) and unburnt building bricks", *Proceedings of the International Conference on Economical Housing in Developing Countries: Materials, Construction Techniques, Components, Paris, January 25-27 1983* (Paris, Presses de l'ENPC, 1983), vol. 1, pp.275-279.

Najmi, D., "Habitat économique en terre dans le Sahara", *Comptes-rendus du colloque international : "Materiaux techniques et économique de la construction dans les pays en développement"*, Paris, 9-10-11 décembre 1986 (Paris, CSTB, Plan Construction, Presses de l'ENPC, 1986), vol. 1, pp.331-337.

Navarro, A., and others, *Comportamiento de las Construcciones de Adobe ante Movimientos Sísmicos* (Lima, Asociación de Asaguradores del Perú, 1972).

Neubauer, L.W., *Adobe Construction Methods* (Berkeley, University of California, 1964).



Newcomb, D.G., *The Owner-built Adobe House* (New York, Charles Scribner and Sons, 1980).

Niameyer, R., *Der Lehmbau, Seine praktische "Anwendung"* (Griebenstein, Oeko, 1982).

"Normas de diseño sismo resistente. Construcciones de adobe y bloque estabilizado", *Capitulo*, No. 6 (Lima, 1977), pp.4-7.

Norton, J., *Building with Earth. A Handbook* (Rugby, IT Publications, 1986).

Norton, J., "Limitations on improving earthquake resistance: the exploitation of local materials. A case study in Guinea-Conakry, *Proceedings of a Symposium held in Bangkok, from 20 to 26 January 1987, on Building Materials for Low-income Housing, Asia and Pacific Region* (London, E. and F.N. Spon, 1987), pp.287-293.

Obi, B.C.A., *Performance Requirements and Basic Details for Use of Soil-cement Blocks* (Kumasi, University of Science and Technology, 1972).

O'Connor, J.F., *The Adobe Book* (Santa Fe, Ancient City Press, 1973).

Odul, P., and Houben, H., "The mutual influence between soil identification tests and standards on earth construction: a question of research priorities and potentialities for application", *Proceedings of a Symposium held in Bangkok, from 20-26 January 1987, on Building Material for Low-income Housing, Asia and Pacific Region* (London, E. and F.N. Spon, 1987), pp.341- 348.

Okie, J.S., *Block Press Handbook for Making Soil Blocks with a "TEK-BLOCK" Press* (Kumasi, University of Science and Technology, 1970).

Oliver, P., *Shelter in Africa* (London, Barrie and Jenkins, 1971).

Olivier, M., *Caractérisation des briques de terre crue compressée par l'essai Proctor statique* (Paris, Rexcoop PCH, 1985).

Olivier, M., and Mesbah, A., "The static compressive test to optimize the mechanical characteristics of compressed raw earth bricks", *Proceedings of a Symposium held in Bangkok, from 20-26 January 1987, on Building Material for Low-income Housing, Asia and Pacific Region* (London, E. and F.N. Spon, 1987), pp.64-71.

Ophoven, P., *Compressive Strength of Walls Built up of Mudblocks and Soil-cement Blocks* (Dar-es-Salaam, Building Research Unit, Ministry of Lands, Housing and Urban Development, 1977).

Osman, M.A., "Laboratory test results on stabilized soils and field studies on rammed earth walls", *Proceedings of a Symposium held in Nairobi, from 7 to 14 November 1983, on Appropriate Building Materials for Low-cost Housing, African Region* (London and New York, E. and F.N. Spon, 1985), vol. 2, pp.61-69).

Osman, M.A., and Mohammed, A.A., "Materials and techniques for wall construction in Sudan", *Proceedings of a Symposium held in Bangkok, from 20-26 January 1987 on Appropriate Building Materials for*



*Low-cost Housing, Asia and Pacific Region* (London and New York, E. and F.N. Spon, 1987), pp.208-212.

Palafitte jeunesse, "Minimôme découvre la terre", (Grenoble, Palafitte jeunesse, 1975).

Patty, R.L., "Paints and plasters for rammed earth walls", *Agricultural Experimental Station Bulletin* (Brookings, South Dakota State College, 1940).

Pereira, H., "Dos edificios públicos a base de tierra en Chile", *La Tierra, Material de Construcción. Informes de la Construcción* (Madrid), vol. 37 (1987), No. 377, pp.23-31.

Pichvai, A., *Vers une architecture antisismique appropriée. Constructions rurales en terre* (Brussels, Institut Supérieure d'Architecture de l'Etat "La Cambre", n.d.).

"Plans de maisons économiques en terre stabilisée", *Bulletin d'information* (Lomé, CCL, 1972), No. 10.

Plencherel, J.M., *Briques en terre séchée revêtue de planelles en terre cuite* (Lausanne, Ecole Polytechnique de Lausanne, 1983).

POC-CSTC, Private communications (Brussels, 1984).

Pollack, E., and Richter, E., *Technik des Lehmbaues* (Berlin, Verlag Technik, 1952).

Poppo Wamy, *Rural India. Village Houses in Rammed Earth* (Stuttgart, Dienst in Übersee, 1979).

Prin, D., and Cubaud, J.C., "La stabilisation des terres et les mécanismes physico-chimiques liés à la cristallisation à froid", *Construire* (Algiers) (1983), No. 2, pp.41-49.

*Proceedings of the International Symposium on Earth Architecture, Beijing, 1-4 November 1985* (Beijing, The Architectural Society of China 1985).

"Producción y ensayos de bloques de suelo prensado", *Boletín*, No. 3 (Asunción, Universidad Católica Nuestra Señora de la Asunción, 1985).

Programa COBE, *Adobe Estabilizado* (Lima, Ministerio de Vivienda y Construcción, 1977).

Programa COBE, *Mejores Viviendas de Adobe* (Lima, Ministerio de Vivienda y Construcción, 1978).

Programa COBE, *Techo Liviano de Caña y Barro* (Lima, Ministerio de Vivienda y Construcción, 1979).

Qasmi, L., "L'utilisation de la terre stabilisée dans la réduction du coût de l'habitat : enseignements et limites de deux expériences marocaines", *Comptes-rendus du colloque international "L'habitat économique dans les pays en développement, matériaux, techniques de construction composants"*, Paris, 25-27 janvier, 1983 (Paris, Presses de l'ENPC, 1983), vol. 1, pp.97-102.

Quadras, A., *Como Hacer Bloques de Suelo-cemento* (Santiago de Chile, Centro Urbano de Asistencia Técnica, 1985).

Ramesh, M., and Allan, R., *Roofing with Mud Bricks. Mud Brick Dome and Vault Constructions: the Maryborough Experience* (Melbourne, Centre for Applied Research on the Future, 1987).

"Recherche habitat saharien : le béton de terre", *Construire* (Algiers) (1983), No.3, pp.32-47.

Reddy, B.V.V., and Jagadish, K.S., "Pressed soil blocks for low-cost buildings", *Alternative Building Series*, No. 10 (Bangalore, ASTRA, Indian Institute of Science 1983).

Rosenak, S., "Rammed earth and stabilised soil for building construction", *Bulletin No. 1* (Rangoon (Yangon), Building Materials Research Institute, 1957).

Rubaud, M., and Chevalier, B., *Etude de différents systèmes de protection superficielle du matériau "terre" utilisé pour la construction* (Paris, Rexcoop, 1986).

Saiyid, Nazir Ahmad, "Durabilité de la terre stabilisée dans les éléments de construction économique", *Communications au séminaire régional sur l'habitat spontané et l'habitat économique. Addis Abeba, 18-21 novembre 1985* (Paris, UNESCO, MUDH, CEBTP, 1987), pp.154-157.

Salas, J., and Moreno, R., "Le domain de la terre, un conjunto de realizaciones-piloto a base de tierra en L'Isle d'Abeau (Francia)", *La Tierra, Material de Construcción. Informes de la Construcción* (Madrid), vol. 37 (1987), No. 377, pp.33-42.

Salmar Nogueira e Taveira, E., *Construir Morar Habitar : o Solo-cimento no Campo e na Cidade* (São Paulo, Icome Editora, n.d.).

Salthner, D., *Les bases de la production végétale* (Angers, Collection Sciences et techniques agricoles, 1982).

Schultz, K.V., *Adobe Craft, Illustrated Manual* (Castro Valley, CA, Adobe Craft, 1974).

Simon, D., *Torture enterre* (Paris, Rexcoop, 1987), tome 3, Couvertures plates.

Simonnet, J., *Recommandations pour la conception et l'exécution de bâtiments en géobéton* (Abidjan, LBTP, 1979).

Simonnet, J., Liautaud, G., and Bamba, B., *Recommandation pour la conception et l'exécution de bâtiments économiques en géobéton* (Abidjan, LBTP, 1980).

Simonnet, J., and Serey, P., "Emploi du béton de terre (géobéton) pour la construction économique en Côte d'Ivoire", *Annales de l'ITBTP* (Paris) (1980), No. 386, pp.105-135.

Smith, E.W., *Adobe Bricks in New Mexico* (Socorro, New Mexico Bureau of Mines and Mineral Resources, 1982).

Smith, R.G., and Webb, D.J.T., *Small-scale Manufacture of Stabilised Soil Blocks* (Geneva, ILO, 1987).

*Solar Earthbuilder International's Earth & Sun* (Las Cruces, NM, ARC, n.d.).



*Solo-cimento na Habitação Popular. Relatório final fase 2. Projeto THABA* (Camagari, Centro de Perquisas e Desenvolvimento, n.d.).

Southwick, M., *Build with Adobe* (Chicago, The Swallow Press, 1971).

"Spécial géobéton", *Bulletin du LBTP* (Abidjan) (1986), No. 3.

Spence, R., *Making Soil-cement Blocks* (Lusaka, Commission for Technical Education and Vocational Training, 1971).

Sperling, R., *Soil-cement Blocks. Effect of Soil Composition on Durability and other Properties* (Accra, West Africa Building Research Institute, 1962).

Stedman, M.L., *Adobe Architecture in New Mexico* (Santa Fe, The Sunstone Press, 1971).

Stedman, M.L., *Adobe Remodeling* (Santa Fe, The Sunstone Press, 1976).

Stulz, R., *Appropriate Building Materials* (St. Gallen, Swiss Centre for Appropriate Technology, 1981).

Svare, T.I., "Soil stabilization. General", *BRU Data Sheet*, No. B.8.1 (Dar-es-Salaam, Building Research Unit, Ministry of Lands, Housing and Urban Development, 1974).

Svare, T.I., and Therkildsen, O., "Soil stabilization. Stabilizer: cement", *BRU Data Sheet*, No. B.8.2 (Dar-es-Salaam, Building Research Unit, Ministry of Lands, Housing and Urban Development 1974).

Taibi, H., and others, "Un matériau pour l'habitat économique : la terre stabilisée par un liant pouzzolanique de synthèse", *Communications au séminaire régional sur l'habitat spontané et l'habitat économique. Addis Abeba, 18-21 novembre 1985* (Paris, UNESCO, MUDH, CEBTP, 1987), pp.132-139.

"Tecnología de construcción en tierra sin cocer", *Revista Especializada en Espacios Educativos*, No. 59-60 (Mexico City, 1983).

THABA, *Cartilha de Construção com Solo-cimento* (Camagari, 1981).

"Tierra para casas habitación", *Folieto*, No. 22 (Mexico City, Centro Regional de Ayudo Técnica, 1964).

Titècat, M., "Pour une politique de promotion cohérente de la construction en terre en Côte d'Ivoire. Plaidoyer pour la filière blocs BTS à Maçonner", *Bulletin du LBTP* (Abidjan) (1986), No. 3, pp.21-39.

Titècat, M., and Sandé, O., "Technologie des essais et gestion de la qualité dans la fabrication de blocs B.T.S. (géobéton). Innovations et recherches en cours", *Bulletin du LBTP* (Abidjan) (1986), No. 3, pp.69-74.

Toukam, J.B., *Etude de marché de presses à parpaings de terre* (Douala-Akwa, APICA, 1986).

United Nations, *Soil Cement, its Use in Building* (New York, 1964).

United Nations Centre for Human Settlements (Habitat), "Construction with sisal cement", *Technical Notes* (Nairobi, UNCHS (Habitat), 1981).



Van Den Branden, F., and Hartsell, T., *Plastering Skill and Practice* (Chicago, American Technical Society, 1971).

Van Dresser, P., *Homegrown Sundwellings* (Santa Fe, The Lightning Tree, 1979).

Vargas Neumann, J., "Las construcciones con tierra, hoy. Una visión desde Latinoamérica", *La Tierra Material de Construcción*, Monografía No. 385-386 (Madrid, Instituto Eduardo Torroja, 1987), pp.107-114.

Vargas Neumann, J., "Preservation of adobe constructions in rainy areas", *Proceedings of the Tenth Triennial Congress of the International Council for Building Research, Studies and Documentation for Shelter for the Homeless in Developing Countries, 22-26 September 1986, Washington* (Gaithersburg, CIB 86, 1986), vol. 4, pp.1457-1465.

Velarde González, J.M., *La Tierra Estabilizada y su Utilización en la Producción de Componentes para la Construcción* (Panama City, Universidad de Panamá, 1966).

Vidolso, A., and others, *Seguir Construyendo con Tierra* (Lima, CRAterre, 1984).

Viñuales, G.M., *Restauración de Arquitectura de Tierra* (Buenos Aires, Editorial del Instituto Argentino de Investigaciones de Historia de la Arquitectura del Urbanismo, n.d.).

Volhard, F., *Leichtlembau* (Karlsruhe, C.F. Muller GmbH, 1983).

Wassé Basharyar, A., and Labasse, D., *Rapport d'évaluation du chantier expérimental* (Bamako, CTA, 1983).

Webb, D.J.T., "Stabilised soil construction in Kenya", *Proceedings of the International Conference on Economical Housing in Developing Countries: Materials, Construction Techniques, Components, Paris, January 25-27 1983* (Paris, Presses de l'ENPC, 1983), vol. 1, pp.137-140.

Webb, D.J.T., and Lockwood, A.J., *BREPAK Operators Manual* (Watford, BRE, 1987).

Weber, C., and others, "Faisabilité de parpaings en latérite-ciment", *Comptes-rendus du colloque international l'Habitat économique dans les pays en développement : matériaux, techniques de construction composants, Paris, 25-27 janvier 1983* (Paris, Presses de l'ENPC, 1983), vol. 1, pp.55-59.

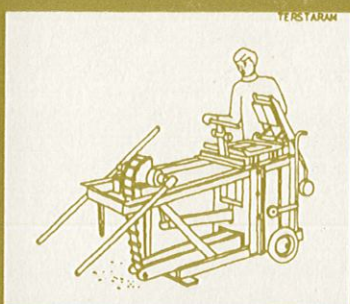
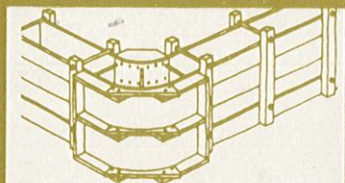
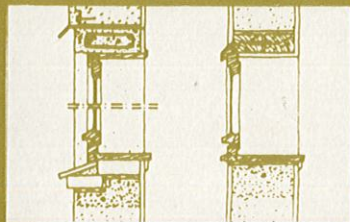
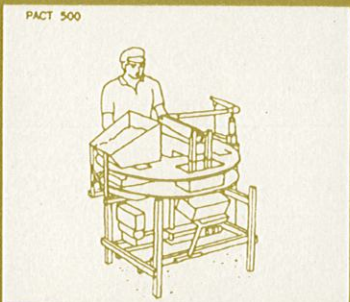
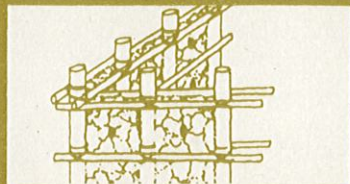
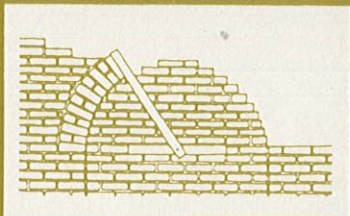
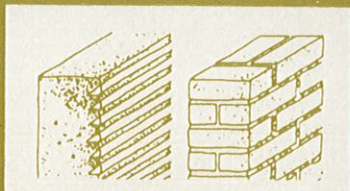
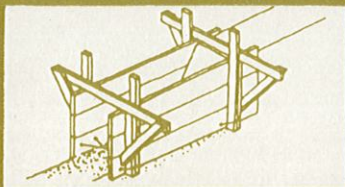
Welsch, R.L., *Sod Walls* (Broken Bow, NE, Purcells Inc. 1968).

Wienands, R., *Die Lehmarchitektur der Pueblos* (Köln, Studio Dumont, 1983).

Williams-Ellis, C., Eastwick-Field, J., and E., *Building in Earth, Pisé and Stabilized Earth* (London, Country Life, 1947).

Wolfskill, L.A., Dunlap, A., and Gallaway, B.M., *Bâtir en terre* (Paris, CRET, n.d.).

Wolfskill, L.A., Dunlap, W.A., and Gallaway, B.M., *Handbook for Building Homes of Earth* (College Station, Texas Transportation Institute, n.d.).



**CRATerre-EAG**  
Centre Simone SIGNORET - BP 53  
38090 VILLEFONTAINE - France



**UNITED NATIONS CENTRE FOR HUMAN SETTLEMENTS (Habitat)**  
P.O. Box 30030, Nairobi, KENYA. Telephone: 230800, 520600  
Cable: UNHABITAT; FAX (254) 2 226473, 226479; Telex: 22996 UNHAB KE